MECHANISM

POPULAR
SCIENCE
BOOKLET SERIES

MECHANISM

Author: Ai Qingchun
Translator: Yao Junde

CHINA SCIENCE AND TECHNOLOGY PRES

From the Editor

The working principles, experiments and utilizations of simple mechanisms, such as lever, pulley, wheel and axle, inclined plane, wedge and screw, are explained systematically with plain examples from our everyday life. Those important concepts of force, mechanical work, capacity and efficiency in physics are discussed from the fundamental point of view of simple mechanism. This booklet is illustrated with interesting pictures and diagrams and its language is clear, lively and easy to understand. It is suitable for readers of junior middle school educational level.

MECHANISM is one of the "Popular Science Booklet Series" which has a total of twelve booklets, namely: Mechanism, Sound, Heat, Electricity, Air and Water, Light, Astronomy, The Earth's Crust, Meteorology, Animals, Plants, Physio-Hygiene.

Popular Science Booklet Series

MECHANISM

Author Ai Qingchun
Translator Yao Junde

China Science and Technology Press

First Edition 1985

Published by CHINA SCIENCE AND TECHNOLOGY PRESS
32 Baishiqiao Road, Beijing, China

Printed by THE FOREIGN LANGUAGES
PRINTING HOUSE
19 West Chegongzhuang Road, Beijing, China

Distributed by the China International Book Trading
Corporation (GUOJI SHUDIAN)
P.O. Box 399, Beijing, China

Printed in the People's Republic of China

CONTENTS

CHAPTER I

SIMPLE MECHANISM

In our daily work and labour, we use machines here and there at any time. On a worksite, a lofty crane can raise a huge and heavy cement plate high up into the air in an easy manner; on a highway, a speeding bus is carrying passengers to their destination timely; in a factory, a sewing machine can make a nice and beautiful dress out of well-cut materials. Cranes, buses and sewing machines are machines. Making use of machines in place of manual labour is an easy and speedy way in doing our work and also it saves a lot of labour. The quality of the work done by machines is much better than by manual labour. Machines are efficient tools for human beings (Fig. 1).

Lift up the bonnet or hood in the front of a car and examine the interior structure, what a dazzling sight! Such a lot of machine parts in various shapes were assembled together.

Generally speaking, all machines are complicate, especially those modern heavy-duty machines, which are very complicate indeed.

But after careful examination of the structure of various machines, one will find that no matter how complicate a machine may be, it is always consisted of a certain number of

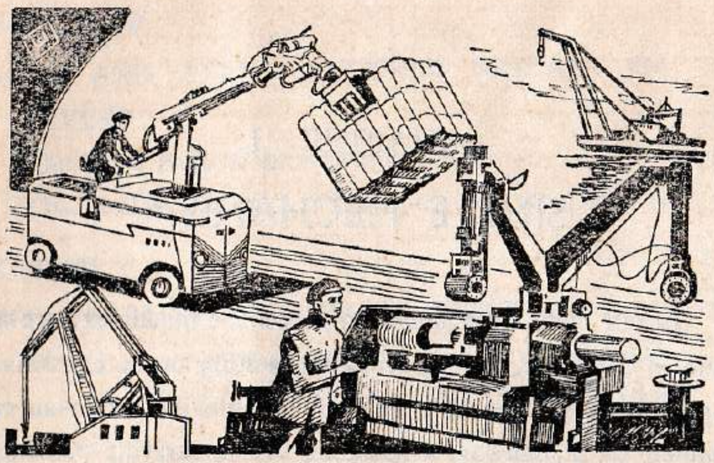

Fig. 1 Machines are efficient tools for human beings

very simple and basic component units. These simple and basic component units can help us not only to change the magnitude of force applied but to change its direction as well. People called these components which can change the magnitude of a force and its direction *simple mechanism* or just *mechanism* in the following description.

It is very important to master the principle of mechanism in order to understand and make use of those complicate machines. What are their shapes? Have you ever seen them before? Have you ever made use of them before?

Everyman Is an "Expert" in Applying Mechanism to Use

People may not be good at operating a crane, driving a car or making use of a sewing machine. But one has been using

mechanism since at the age of two or three years old. So, every one of us are all good at applying mechanism to use.

Children are fond of playing at seesaw. A seesaw is a mechanism. Pulling a flag up a flagpole is also an application of mechanism to use. The man pulls a rope in a downward direction, and the flag rises slowly upward. Actually, there is a pulley at the top of the flagpole. This pulley is a mechanism (Fig. 2). Listening to a radio or watching television, people have to turn a switch. The switch is a mechanism. In winter, after a heavy snow, the mountain is covered with a layer of silver-white snow, people will happily carry a pair of skiis and go skiing. People may not realize that when they are skiing down the slope, the mountain slope under their feet is actually a mechanism too (Fig. 3). Mechanism appears in our daily life everywhere, and we are applying mechanism to use everyday. There are times when people can hardly live without mechanism. Now, how much do we know about mechanism?

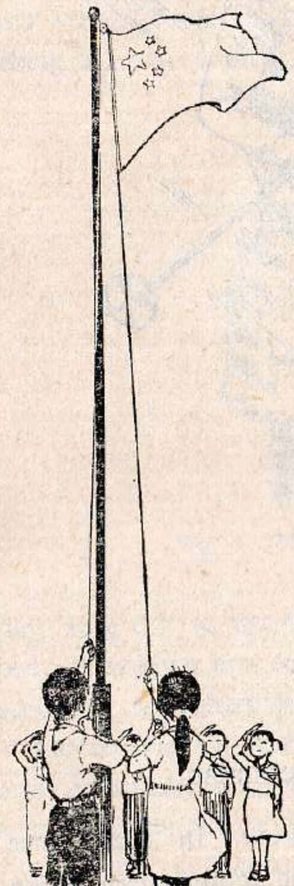

Fig. 2 Hoisting a flag

Fig. 3 Skiing

A Brief History of Mechanism

Mechanism has a long, long history. In 1929, some Chinese archaeologists discovered in the southwestern region of Peking the fossils of an Ape-man's skull, teeth, lower

jaw and limbs, living a half million years ago, in a cave at a place named Zhoukoudian. This is one of the earliest and most reliable evidence of the discovery of mankind in the world at present. This ape-man is named Peking Man (*Sinanthropus Pekinensis*) (Fig. 4). This discovery shows that mankind has a history of at least more than five hundred thousand years. From the fossils excavated, it shows that the Peking Man lived in a cave formed in the calcareous rock.

Fig. 4 The Head of Peking Man

They were able to use wood to make a fire for cooking their food. They knew how to select gravel stones or quartz to make stone flints with sharp edges to be used as weapons or tools for production (Fig. 5). These weapons or tools can be considered as the embryonic form of simple mechanism. The stone chisel is just like the axe in the present time.

In 1954, in Shanxi Province in China, people discovered the fossil remains of an ape-man — named "Dingcun Man" — and a large amount of stone implements.

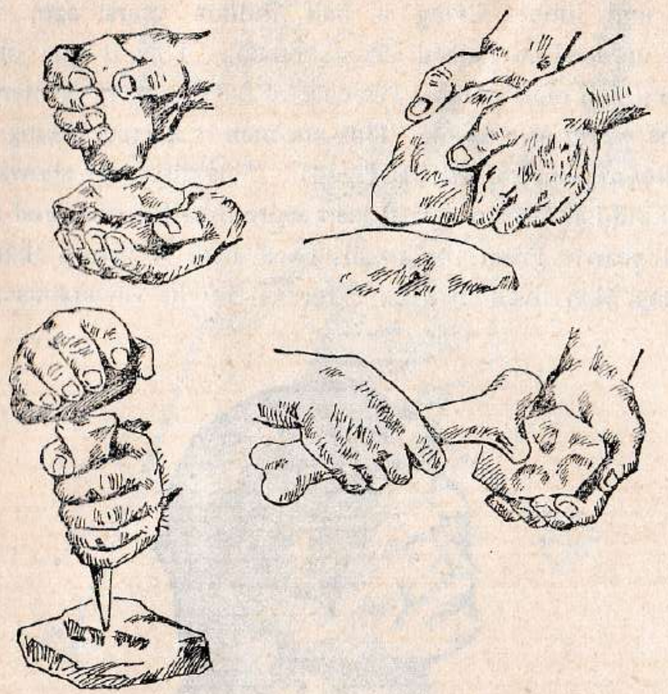

Fig. 5 The stone implements used by Peking Man

According to the analysis of the archaeologists, *Dingcun Man* lived about 300,000 years ago. They were much more progressed than the *Peking Man.* The stone implements used by them included sharp-pointed implements, long scrapers and various other kinds of scrapers. These tools are all better than those used by the *Peking Man.* These stone implements are the earliest mechanism.

Later on, in China's Northwest, North China, Northeast and Southwest, fossil remains and stone implements used by primitive men were also discovered, revealing the successive evolutionary stages of mankind. It is undoubtedly that 500,000 years ago, there were human beings, living and creating their own cultural life in various regions within the territory of China.

The fossil remains of human bones dated 100,000 years ago and their stone implements, bone implements and decorative objects excavated in China are quite similar to the stone implements excavated in Western Europe. We may conclude that, right after the early men surpassed the animal stage, they began creating and making mechanisms from the first days of their labour. Therefore, the history of mankind is also the history of mechanism development.

From the written history of mankind, in ancient China, people learnt to use a lever cleverly with a relatively well understanding of its principle. About 3,000 years ago, people used a mortar to pound paddy and used a jiegao (a weight-lifting device) to lift water from a well. They were able to make and use a steelyard or scales (Fig. 6).

"Mo Jing", the classics written from the 4th to the 3rd century B.C., exquisitely described the lever rule.

Being the earliest book written on mechanism, this book is like a precious pearl glittering in the scientific and cultural treasure-house of mankind.

People all over the world have made their contributions in the development and utilization of mechanism through practice. It is worthwhile to note that the Greek philosophers Aristotle (384 — 322 B.C.) and Archimedes (287 — 212 B.C.) had summarized a number of laws concerning the balance of a lever.

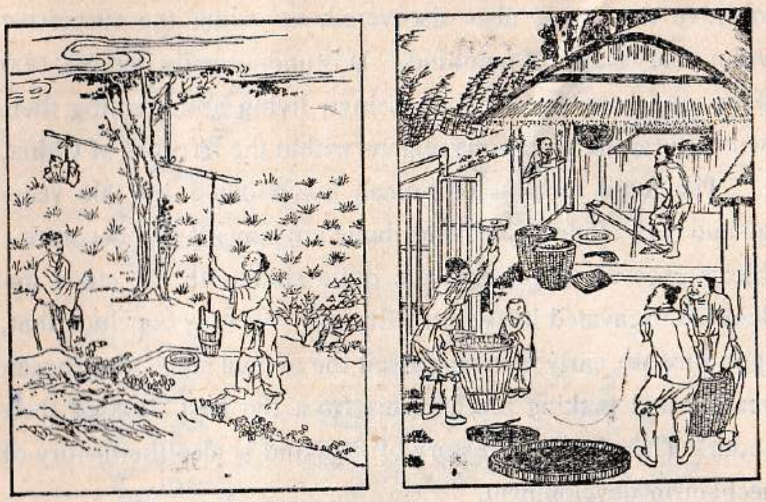

Fig. 6 A mortar, a jiegao

In keeping with the social development and production needs, people became more consciously in summarizing their own experiences, created and invented many new and more efficient mechanisms, so that greater benefits gained for less time and cost. For example, people make use of wind power, water power and animal power to drive windmills and waterwheels for irrigation and corn grinding. In so doing, it saves a lot of time and energy as compared with doing it by manual labour. Windmills, waterwheels and grinders are examples of applying mechanism to use, and they were perfected gradually. A simple horse-drawn carriage may be considered as the integrate utilization of mechanism. The improvement of ancient weapons, such as bows and arrows as well as swords and spears can also be considered as the incessant development of the use of mechanism.

But, the utilization and creation of mechanism through the production practices of mankind was done in a blind and crude way for quite a long period. No systematic knowledge had been gained about the working laws concerning mechanism.

In the 17th century, owing to the rapid development of production in Europe, the textile industry and the machine building industry grew in a tremendous speed. And in the meantime, due to the need for navigation and war, the creation of astronomy and mechanics was promoted. During this period, new methods for observation and new means for doing experiments were gradually found and perfected. Sir Isaac Newton (1642 — 1727), the great British scientist, systematically summarized the laws of mechanics known at that time. In the subsequent two to three hundred years, mechanism was perfected day by day. Thus, a precise science was established. James Watt (1736 — 1819), a British worker technician, improved the steam engine, making it driving various kinds of machines continuously. From then on, locomotives, automobiles and even aeroplanes were invented successively and were widely employed. In our modern life, mechanism occupies an even more important position.

Since the beginning of the 20th century, the development of science and technology has been progressing in giant strides. Some of the new scientific theories and ideas demand an even newer and higher development of mechanism. The peaceful use of atomic energy, the invention of laser and the newly emerged astronautic explorations all require the knowledge of mechanism. Atomic reactors, nuclear power stations,

atomic ice-breakers and submarines, supersonic jet aeroplanes, spacecrafts, rockets, laser drilling and laser surgery are all integrated mechanisms.

The more science and technology advanced, the more things unknown people desired to explore. The task of exploiting the vast universe is really a challenging one. And the structure below earth surface is still not quite known to us. The basic structure of matter is yet in the stage of supposition. The synthesis of life needs much deeper study. . . . It is beyond doubt that all these will present even harder tasks for the development of mechanism before men.

It is quite obvious too, that mechanism with its age-long history in the past will have an even brighter future (Fig. 7).

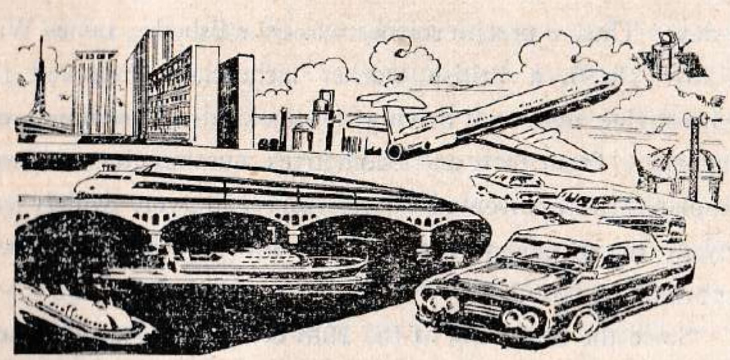

Fig. 7 The modern world

How Many Kinds of Mechanism Are There?

How many kinds of mechanism are there? Apart from the things mentioned above, a pair of scissors, a seesaw, a pulley,

a switch or a slope, one can name many more things, such as, a balance for weighing things, a chopper for cutting straw, a wheelbarrow for transporting earth, a claw hammer for pulling out a nail, a windlass for lifting water often seen in the countryside, a screwdriver for driving in a screw, an axe for cleaving wood and also a small screw are all mechanisms (Fig. 8).

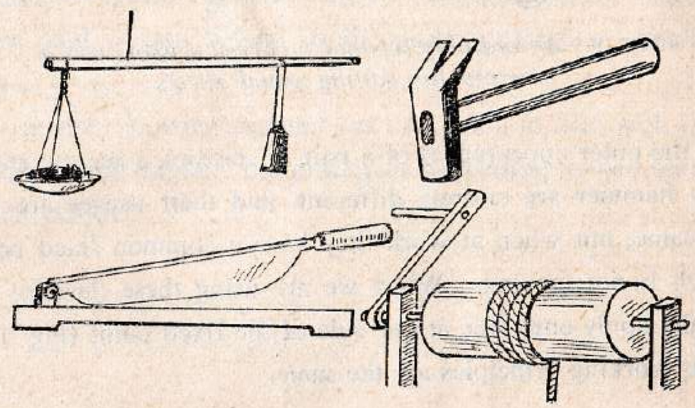

Fig. 8 A balance, a chopper, a claw hammer and a windlass

Taking a pair of scissors for example, there are many kinds of them. Some are used for cutting papers or iron sheets; others like the curved scissors are used for surgical operations (Fig. 9). There are so many kinds of mechanisms that no one could tell just how many there are.

But after studying it carefully, no matter how complicate the shapes of the mechanism are and no matter how different the usage of the mechanism is, there are still many aspects in common. These common aspects are very important. For exam-

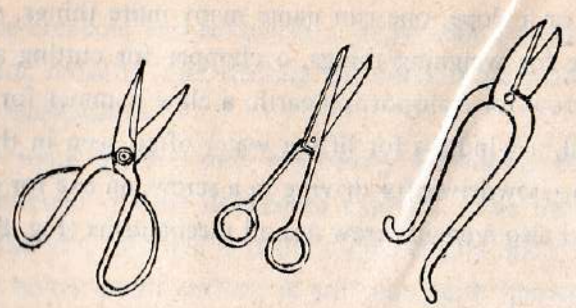

Fig. 9 An ordinary scissors, a curved scissors and a scissors for cutting metal sheets

ple, the outer appearances of a pair of scissors, a seesaw and a claw hammer are entirely different, and their usages are not the same, but when at work they have a common fixed point which is not moving. When we are using these devices, we usually apply our force at one side of the fixed point (Fig. 10). Their working principles are the same.

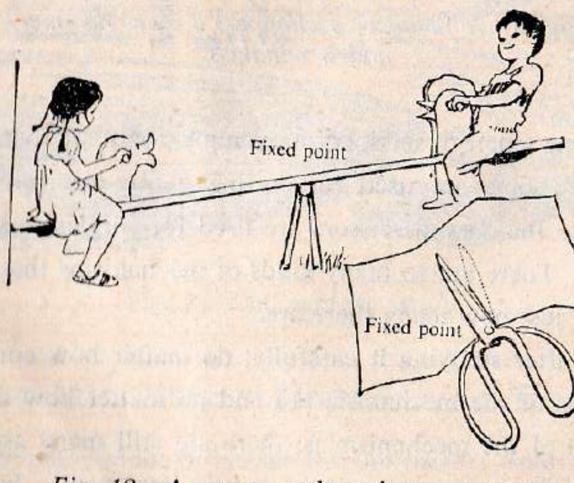

Fig. 10 A seesaw and a scissors at work

Let us find out the common points from these mechanisms of different varieties. It is not difficult to classify some of those main mechanisms into two main categories. One is called *lever*, and the other is called *inclined plane.*

Scissors, seesaws, balances, choppers, wheelbarrows, claw hammers, switches, windlasses and pulleys belong to the first category — *levers.* Slopes, axes, swords, sabres, shovels, picks, and screws belong to the second category — *inclined planes.*

In the following chapters, we are going to deal with these problems and explain the principles concerning levers and inclined planes.

CHAPTER II

A LEVER

It is not an easy matter to move a rock weighing several hundred kilograms by hands. But, putting one end of a long wooden rod at the bottom of the huge rock and putting a small rock under the rod some point near the huge rock, and then pressing another end of the rod down energetically, the rock can be moved by one man (Fig. 11).

Let's study the process of prying up a huge rock with a wooden rod or a crowbar. When the man presses hard with his hand at one end of the crowbar, on receiving a downward force from the hands, the crowbar at this end will move down-

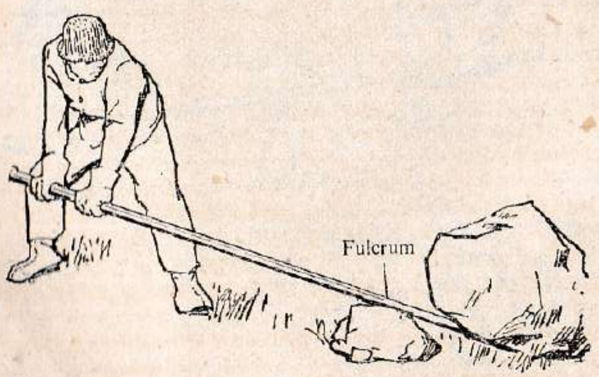

Fig. 11 Prying up a huge rock

ward. In the meantime, the other end of the crowbar under the huge rock bearing a downward pressure from the rock exerted an upward force. The momentums of these two forces are the same, but the directions of these two forces are opposite to each other. In physics, this phenomenon is called action and reaction. The whole crowbar, except the fixed point at the small rock is not moving, rotates around the fixed point as the huge rock is being pried up.

By using a claw hammer, it is quite easy to pull up a nail which had been driven into a wood (Fig. 12). The claw hammer

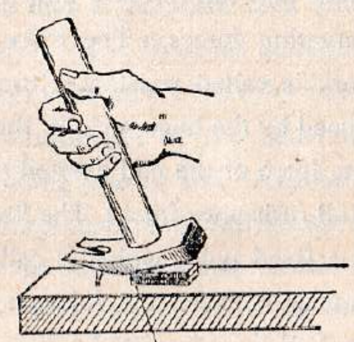

Fig. 12 A claw hammer pulling a nail

is working like this way: Fix the claw of the claw hammer to the flattened head of a nail and put the other end of the hammer on the table as a fulcrum, and then pull the handle of the hammer toward the direction of the rounded end of the hammer. A force is applied to the handle, so, at the same time, a force is produced at the end of the claw to pull the nail up. In the

process of pulling a nail up, except the point where the head of the hammer rests does not move, the whole body of the hammer rotates around the fulcrum.

A crowbar and a claw hammer produce the same typical effect as a lever.

The Working Principle of a Lever

In general, the force applied purposely to actuate the mechanism is called actuating force. For instance: the force to press the crowbar and the force to pull the claw hammer's handle are all actuating forces. The force that hinders the mechanism to work is called resistance force. For instance: the pressure produced by the huge rock on the end of the crowbar and the pulling force of the nail exerted on the claw of the claw hammer are all resistance forces. The lever at work usually rotates around a fixed point which is called fulcrum. The perpendicular distance between the fulcrum and the straight-line path of the applied force is considered to be the arm of the actuating force, so it is called the actuating arm. The perpendicular distance between the fulcrum and the straight-line path of the resistance force is considered to be the arm of the resistance force, so it is called the resistance arm (Fig. 13).

People may have such an experience that one must apply a greater force to the crowbar in order to move a heavier rock. It is obvious that for a fixed-length crowbar, when the fulcrum is fixed, there is a relation between the magnitudes of the actuating force and the resistance force. Some people may have

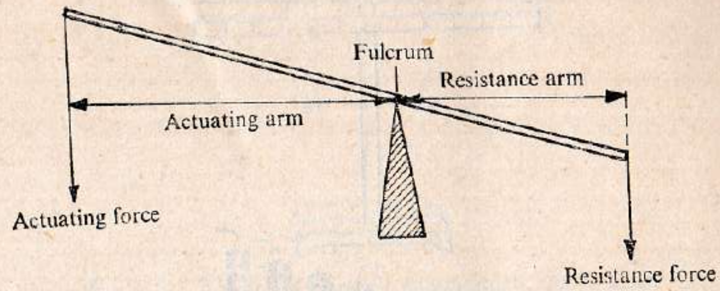

Fig. 13 The actuating force, the resistance force, the actuating arm and the resistance arm

another experience that if the small rock (the fulcrum) under the crowbar is farther away from the actuating force, one may move the huge rock more easily. To be exact, there is a relation between the magnitude of the actuating force and the length of the actuating arm or the resistance arm. If the resistance force is fixed (constant), the longer the actuating arm is, or the shorter the resistance arm is, the less the actuating force is required. How are the actuating force, the resistance force, the actuating arm and the resistance arm related to each other? We can find it out by doing some experiments.

Drill a small hole in the middle of a ruler with scales marked on it. This ruler is to be used as a lever. Hang the ruler onto a framework on a nail through the small hole, so that the ruler can rotate around the nail freely. The nail is the fulcrum of the lever. Everytime before doing the experiment, one must notice that the lever should be placed in a levelling state steadily (Fig. 14).

Prepare several weights for the experiment: weighing 50

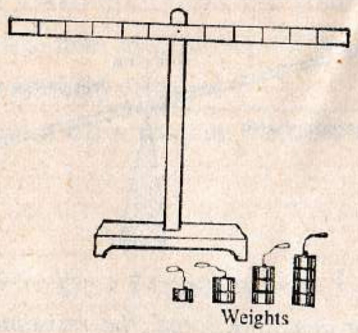

Fig. 14 An experiment on a lever

grams (two pieces), 100 grams, 150 grams and 200 grams each. Attach a string to every weight to be hung onto the lever. When the weights are hung on the lever, the forces that act on the lever by the strings are either actuating forces or resistance forces. The magnitudes of the forces are the weight of the weights in a downward direction.

Let's assume that the weights hanging to the left of the fulcrum act as a resistance force, and that to the right act as an actuating force. (Fig. 15)

First, hang a 50-gram weight 1 cm to the left of the fulcrum. As a result, the weight will turn the levelled crowbar around. In order to keep the levelled crowbar at the original place, where shall we hang another 50-gram weight to the right of the fulcrum? The experiment proved that the position of the actuating force must be 1 cm to the right of the fulcrum so as to balance the crowbar. Since the crowbar is kept in a levelling state again, the direction of the actuating force and the resistance force points downward. At present, the lengths of

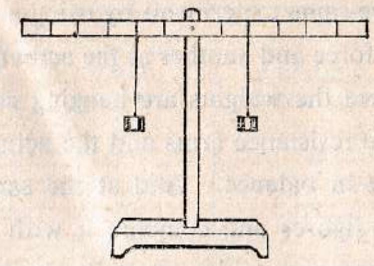

Fig. 15 The equilibrium experiment of a lever

the actuating arm and the resistance arm are all 1 cm long. When the length of the resistance arm varies from 2 cm to 3 cm, 4 cm . . . find the corresponding length of the actuating arm respectively so as to keep the lever in balance, and record the data of the actuating arm in the following table, the data of the experiment in the table must be as follows:

A Table of Data of Lever Equilibrium Experiment

No. of exp.	Fulcrum's left side		Fulcrum's right side	
	resist. force (g)	resist. arm (cm)	actuating force (g)	actuating arm (cm)
1	50	1	50	1
2	50	2	50	2
3	50	3	50	3
4	50	4	50	4
5	50	5	50	5
6	50	6	50	6

Continue the same experiment by using a 100-gram weight as the resistance force and another as the actuating force, change the position where the weights are hanging and then find out the lengths of the resistance arms and the actuating arms when the lever is kept in balance. And at the same time, fill the table with these figures and compare it with the former one. The figures in these two tables are quite similar to each other. These pairs of figures in the tables show clearly that when the actuating force is the same as the resistance force, the lever could be kept in balance only if the length of the actuating arm is the same as that of the resistance arm.

Let's proceed the experiment in a more complicated way. Use a 200-gram weight hung on the left of the fulcrum, and use a 50-gram weight, a 100-gram weight, and a 150-gram weight respectively hung on the right of the fulcrum as the actuating force. When the resistance force acts at the position 1 cm away from the fulcrum, and then use the three weights one by one to find out their respective lengths of the actuating arm so as to keep the lever in balance. Afterwards, change the position of the resistance force from 2 cm to 3 cm, 4 cm . . . and use the three different weights to find out their corresponding lengths of the actuating arm respectively, so as to keep the lever in balance. Record these data in the following blanks in the table.

If the experiment has been done correctly, the figures appeared in the table should be as follows:

By analysing the data in the above table, we can find out the following facts:

No. of exp.	Fulcrum's left side		Fulcrum's right side	
	resist. force(g)	resist. arm (cm)	actuating force (g)	actuating arm (cm)
1	200	1	50	
2	200	1	100	
3	200	1	150	
4	200	2	50	
5	200	2	100	
6	200	2	150	
⋮	⋮	3	⋮	

(1) If the actuating force is not equal to the resistance force, the length of the actuating arm must not be equal to the length of the resistance arm.

(2) If the resistance force remains the same, when the length of the actuating arm is longer than that of the resistance arm, a smaller actuating force as compared with the resistance force can keep the lever in balance; and when the actuating arm is shorter than the resistance arm, a greater actuating force must be applied to keep the lever in balance as compared with the resistance force.

(3) If the length of the actuating arm is n times that of the resistance arm, to keep the lever in balance, the actuating force must be 1/n times of the resistance force. In other words, the actuating force divided by the resistance force must

A Table of Data of Lever Equilibrium Experiment

No. of exp.	Fulcrum's left side		Fulcrum's right side	
	resist. force (g)	resist. arm (cm)	actuating force (g)	actuating arm (cm)
1	200	1	50	4
2	200	1	100	2
3	200	1	150	$1\frac{1}{3}$
4	200	2	50	8
5	200	2	100	4
6	200	2	150	$2\frac{2}{3}$
7	200	3	50	12
8	200	3	100	6
9	200	3	150	4
10	200	4	50	16
11	200	4	100	8
12	200	4	150	$5\frac{1}{3}$
13	200	5	50	20
14	200	5	100	10
15	200	5	150	$6\frac{2}{3}$

be equal to the length of the resistance arm divided by that of the actuating arm, so that the lever can be kept in balance.

On summarizing the data of the experiments, we can write out the relative equation about the actuating force, the actuating arm, the resistance force and the resistance arm as the lever is in balance. Let F_1 be the actuating force, L_1 be the actuating arm, F_2 be the resistance force and L_2 be the resistance arm, their relationship can be expressed mathematically as follows:

Actuating force × actuating arm = resistance force × resistance arm

or, $$F_1 \times L_1 = F_2 \times L_2$$

or, $$\frac{F_1}{F_2} = \frac{L_2}{L_1}$$

In cases the lever satisfy the above-mentioned relationship, the lever will be kept in balance. Therefore, this equation of relation is called the requirements for the equilibrium of a lever. In physics, this is called the lever rule.

Notes About the Utilization of Equilibrium Requirements

The equilibrium requirements of a lever are obtained through experiments. They are important bases for the study of a lever. When applying the equilibrium requirements of a lever to solving a practical problem, one must pay attention to the following aspects:

(1) The equilibrium requirements of a lever are the conditions required when the lever is in equilibrium. Only if the lever is in balance, the equilibrium requirements can be fulfilled.

What is the equilibrium of a lever? Usually, if the lever is at rest, it means the lever is in equilibrium. But we must know that if the lever is in the state of constant motion along a straight line or around an axis, they are also in equilibrium. The so-called equilibrium of a lever does not mean that the lever only remains motionless in a levelling state or moving along a straight line at a constant speed. When the lever is in an inclined position motionless or moving along a straight line at a constant speed, the lever is also in equilibrium.

That is to say, no matter where the position of the lever is, if the lever is not moving or moving along a straight line at constant speed or rotating at constant speed, the lever is in equilibrium and the equilibrium requirements of a lever can be applied to analyse the working condition of a lever.

(2) It is necessary to find out all the forces acting on the lever. Sometimes, there are many forces acting on the lever. We must analyse every one of them to see which one is the actuating force and which one is the resistance force. According to the usual practice, we call the force that operates the lever "the actuating force" and the force that reacts against the actuating force "the resistance force". If there are more than two forces acting on the lever, the one that has the same effect as the actuating force can be regarded as actuating force, and the one that has the same effect as the resistance force is considered as resistance force. Then we must try to find out their respective arms, and finally we can apply the equilibrium requirements to analyse the lever.

For example, the lever shown in Fig. 16 is in balance.

F_1 and F_2 are the actuating forces; L_1 and L_2 are the actuating arms; f_3, f_4 and f_5 are the resistance forces; and l_3, l_4 and l_5 are the resistance arms. The equilibrium requirement is as follows:

$$F_1 \times L_1 + F_2 \times L_2 = f_3 \times l_3 + f_4 \times l_4 + f_5 \times l_5$$

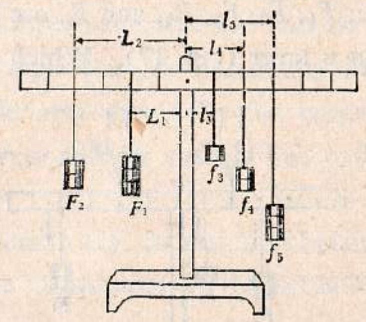

Fig. 16 A lever with five forces act on it

But under certain circumstances, it is rather difficult to distinguish which one is the actuating force and which one is the resistance force. For instance, when we use the weights to do experiments by hanging them onto the lever, by what reason we can say that the weights hanging to the left of the fulcrum are actuating forces and that to the right are resistance forces? Actually, these are only our arbitrary judgment. Under such circumstances, if it is not restricted by the usual practice, the rules for determining the actuating force and the resistance force are not so strict, for they are relative to each other. Once a force is ascertained as the actuating force, then the forces opposite to it can be ascertained as resistance forces.

What is the resultant effect of an actuating force or a resistance force? "Resultant force" means that those forces that can turn the lever around a fulcrum in the same direction are of same resultant effect. It is not decided by whether the force is to the left or to the right of the fulcrum, neither decided by whether the direction of the forces are the same or not.

For example: F_1, F_2, F_3, F_4, and F_5 are five forces acting simultaneously on a lever (Fig. 17). Which of them is of the

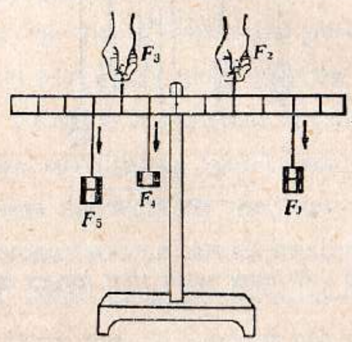

Fig. 17 Which of them are of the same resultant effect

same resultant effect? F_1 and F_3 can turn the lever in a clockwise direction, and F_2, F_4 and F_5 can turn the lever in a counter-clockwise direction. Therefore, F_1 and F_3 are actuating forces (or resistance forces), and F_2, F_4 and F_5 are resistance forces (or actuating forces).

(3) Be careful to calculate the length of the arms when we are making use of the equilibrium requirements. As the actuating forces and resistance forces are ascertained, we have to stick to it without changing through out our calculation. The respective names for their arms are thus ascertained at the same

time. For each of these different forces, there is an arm of its own.

Don't think that the length of the arm is just the distance between fulcrum and the point where the force is applied. That is to say, the length between the fulcrum and the point where the actuating force applied is not necessarily the actuating arm; and the length between the fulcrum and the point where the resistance force applied is not necessarily the resistance arm. The length of the arm should be the perpendicular distance between the fulcrum and the straight-line path of the force applied.

The four levers in Fig. 18 are all in balance. Try to point out rightaway the magnitudes of the actuating forces and the

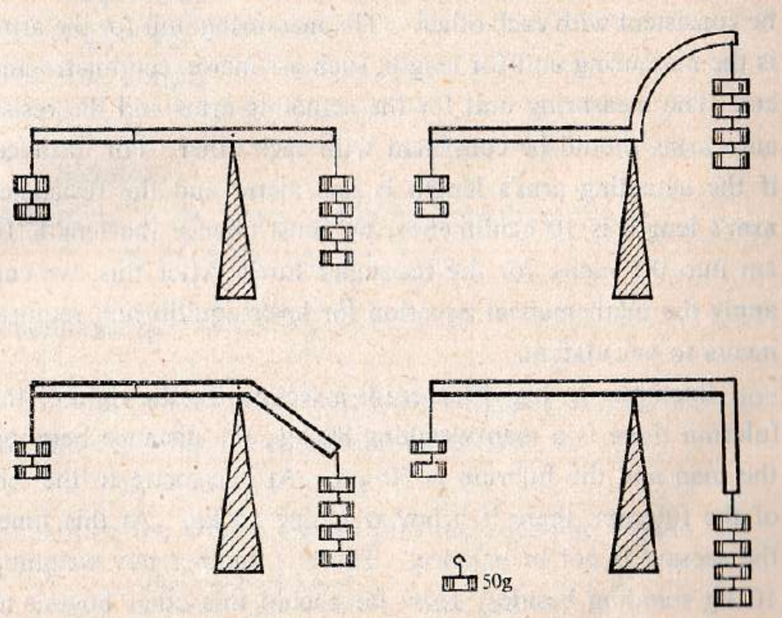

Fig. 18 Four levers in balance

resistance forces, and the lengths of the actuating arms and the resistance arms, then write out the respective equilibrium requirements.

(4) Pay attention to the measuring unit used for the forces and the arms. We must use the same measuring unit for the actuating forces and the resistance forces, and the same measuring unit for the actuating arms and the resistance arms. For the forces, we may use newton, gram, or kilogram (the force of 1 kilogram = 9.8 newton) as the measuring unit. If we use newton as the measuring unit for the actuating force, the resistance force must use the same measuring unit. If we use kilogram as the measuring unit for the actuating force, the resistance force should use the same measuring unit. They should be consistent with each other. The measuring unit for the arms is the measuring unit for length, such as: metre, centimetre and etc. The measuring unit for the actuating arms and the resistance arms should be consistent with each other. For instance, if the actuating arm's length is one metre and the resistance arm's length is 10 centimetres, we must change the length 10 cm into 0.1 metre for the resistance force. After this, we can apply the mathematical equation for lever equilibrium requirements to calculation.

Example: In Fig. 19, there is a seesaw. To the right of the fulcrum there is a man weighing 80 kg., the distance between the man and the fulcrum is 50 cm. At one metre to the left of the fulcrum, there is a boy weighing 15 kg. At this time, the seesaw is not in balance. There is another boy weighing 10 kg standing beside. How far should this other boy sit to the left of the seesaw?

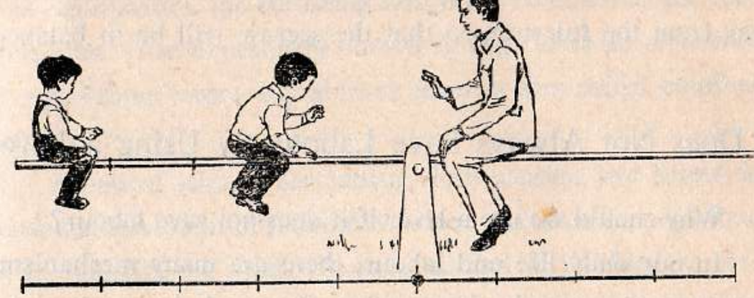

Fig. 19 How to calculate the equilibrium equation of a seesaw

We know:

$F_1 = 80\text{kg}$

$L_1 = 50\text{cm}$

$F_2 = 15\text{kg}$

$L_2 = 1\text{m}$

$F_3 = 10\text{kg}$

Find L_3

Solution:

According to the lever equilibrium requirements,

$$F_1 \times L_1 = F_2 \times L_2 + F_3 \times L_3$$

Therefore, $L_3 = \dfrac{F_1 \times L_1 - F_2 \times L_2}{F_3}$

Before substituting those known figures into the equation, we have to unify the measuring units first.

$L_1 = 50\text{ cm} = 0.5\text{ m}$

Substitute the known figures into the equation, we get

$$L_3 = \frac{80 \times 0.5 - 15 \times 1}{10} = 2.5\ (\text{m})$$

Answer: The other small boy should sit at the place 2.5 m away from the fulcrum, so that the seesaw will be in balance.

It Does Not Always Save Labour By Using a Lever

Why should we use a lever if it does not save labour?

In our daily life and labour, there are many mechanisms made according to the lever rule. Some of the mechanisms enable us to use a smaller force to do a job which needs a greater force. For instance, use a crowbar to lift a rock, or use a steelyard to weigh a heavy object. But some of the mechanisms do not save labour, and at the same time, do not require a greater force. Such as, a pair of scissors to be used to cut papers or a piece of cloth. People don't mind whether it saves labour or not. If it is more convenient to do the job, that will do. Sometimes, the mechanism is designed for a special use, and it may need a greater force to do the job in order to obtain a better and specific result, such as: a clipper for haircut, a curved scissors for surgery. So a lot of non-labour-saving lever devices are made for practical needs.

From the point of view of labour-saving or non-labour-saving, we can divide the levers into three categories: equal-force lever, labour-saving lever and non-labour-saving lever.

(1) Equal-force Lever: A pair of scissors for cutting cloth, a beam balance and a seesaw for children are equal-force levers.

From the lever equilibrium requirements, we know that if the actuating force is equal to the resistance force and the lever

is in equilibrium, the actuating arm must be equal to the resistance arm. The experiment shown in Fig. 15 is an experiment of equal-force lever. Equal-force lever is also called equal-arm lever.

A pair of scissors for cutting cloth consists two levers connected at one point in the middle where the rivet is. The length of the handles are about the same as that of the blades. As to every lever, they are all equal-arm. Therefore, a pair of scissors for cutting cloth is an equal-force lever. The things cut by this kind of scissors are not very hard. The resistance force produced by cutting the cloth is the same as the actuating force produced by the grasp of the hand on the handles. Cutting cloth with scissors does not save labour or needs more force. Fig. 20 shows the picture of the forces acting on the handles and the blades.

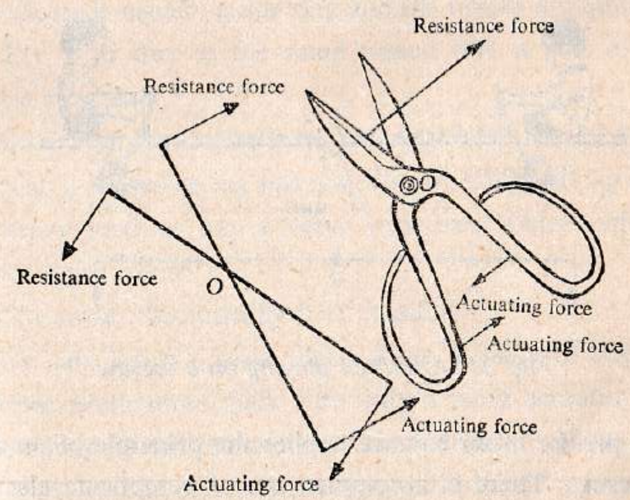

Fig. 20 The forces acting on the scissors

The reason why it is possible for the scissors to cut the cloth is because the force applied by hand to the handles is bigger than the force from the cloth acting on the blades. Therefore, the levers are not in equilibrium. So that the blades closed and the cloth was cut into two.

For the same reason, two little children of same weight sitting at the same distance away from the fulcrum with one to the right and the other to the left will set the seesaw in balance. If they want to make the seesaw go up and down, they have to stamp the ground with their feet when one of them reaches the ground. In so doing, one child may decrease the pressure on the seesaw by stamping the ground so that the equilibrium of the equal-arm lever is upset. One end of the seesaw will go upward and the other end will come down. They stamp the ground by turns, and set the seesaw in motion (Fig. 21).

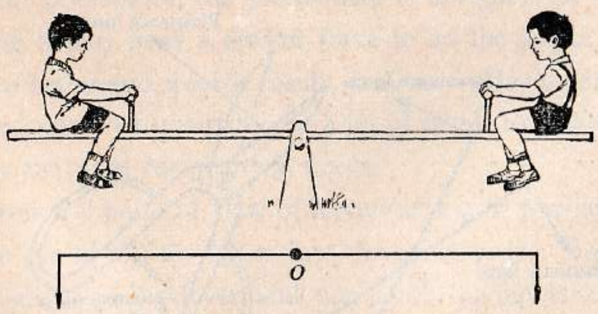

Fig. 21 Children playing on a seesaw

A precise beam balance applies the principle of an equal-force lever. There is a complete set of complicate electronic circuits designed to control the device.

(2) Labour-saving lever: A pair of plate shears and a pair of pliers are all labour-saving levers. To split a piece of iron sheet or to break a steel wire is not an easy job. It needs a greater force. We can't do it just bare-handed. Those lever mechanisms designed in order to save labour are all labour-saving levers.

According to the lever equilibrium requirements, if the actuating force is smaller than the resistance force, the actuating arm of the lever must be longer than the resistance arm in design so as to keep the lever in equilibrium.

As we cut a piece of iron sheet with a plate shears, the iron sheet is rather hard, so the force acting on the blades (resistance) is rather great. In order to cut the iron sheet with a smaller actuating force, the actuating arm of the shears must be designed longer than the resistance arm. Therefore, the handle of the shears is usually quite long and the blades are quite short (Fig. 22). It is due to the same reason that a pair of pliers breaks a steel wire.

Since a labour-saving lever can save labour, why couldn't we design a labour-saving lever so that we could lift up a very, very heavy load or cut a very, very hard object with just "feather light" force?

Of course, theoretically it is possible.

We can design a plate shears to cut a piece of steel plate of several centimetres thick with only a small actuating force. But how long should the handle of the shears be? If the handle is too long, the shears are too heavy, and it is not convenient to use it. It is most important that if the handle is too long, the

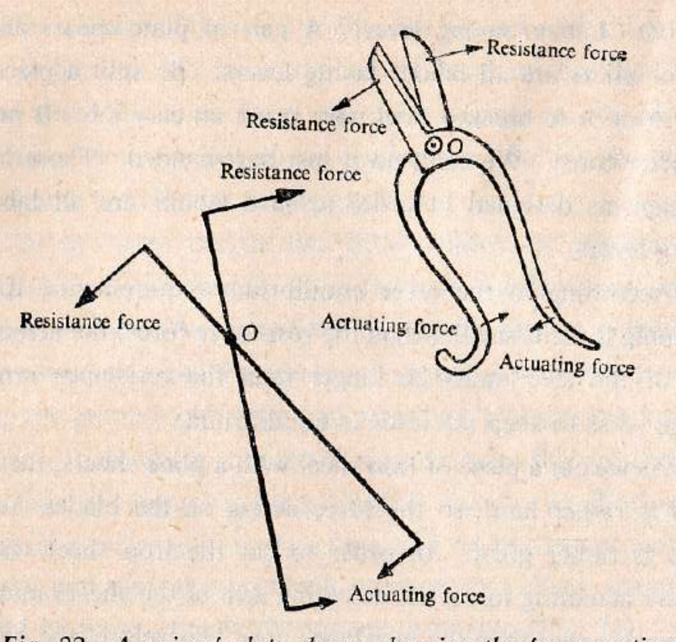

Fig. 22 A pair of plate shears showing the forces acting on the device

acting point of the actuating force should move a long distance and then the acting point of the resistance force could move only a very short distance. It is indeed not economical.

Likewise, we can design a crowbar with an actuating arm much longer than the resistance arm. Of course, we can save quite a lot of labour. It was just like what a famous ancient Greek mathematician Archimedes had said: "Give me a fulcrum, I can lift up the earth." It shows how mighty the lever is. But how long should this lever be? It is beyond imagination.

It is important to study the labour-saving lever. We will

deal with it later on in Chapter V "Mechanical Work and Its Principle" in detail.

(3) Non-Labour-Saving Lever: A clipper for hair-cut, a curved scissors for surgery, a fishing rod and a protruding rod for pulling up a fishing net are all non-labour-saving levers (Fig. 23).

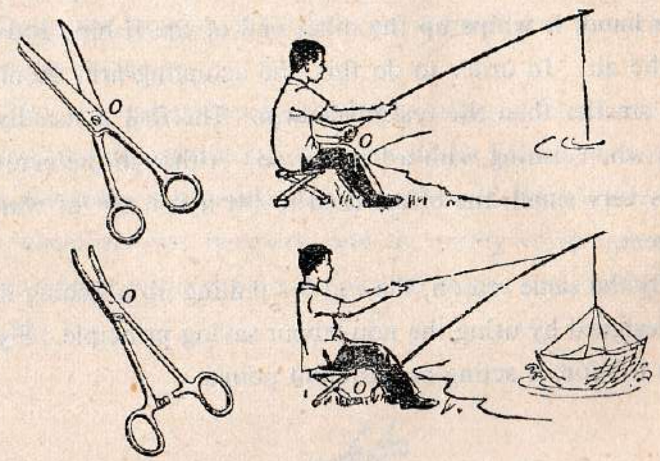

Fig. 23 A clipper, curved scissors, a fishing rod and a protruding rod for a fishing net

Those levers with a smaller actuating arm as compared with the resistance arm are non-labour-saving levers.

Those clippers or scissors are used to cut those objects such as hairs, muscles which are soft matters. It is not necessary for us to pay more attention to how to save labour. When a clipper is at work, it should be easy to handle, swift in motion, and convenient for hair-cutting without much effort. When curved scissors are at work, the hand that holding the handle should

be kept a little farther away from the wound so that the wound may not be infected during operation, and at the same time, the motion of the hand should be kept in a very small range. They are all designed with long sharp blades and short handles.

Fishing with fishing rod is another example. When a fish bites the bait, it is necessary to lift the fish immediately out of water so as not to let it escape. With a slight and quick move of the hand, it whips up the other end of the fishing rod high into the air. In order to do this, the actuating arm should be much smaller than the resistance arm. The fish is usually not so big when fishing with a fishing rod. Although the actuating arm is very small, the effort used to lift a fish out of water is not great.

By the same reason, the rod for pulling up a fishing net is also designed by using the non-labour-saving principle. Fig. 24 shows the forces acting on different points.

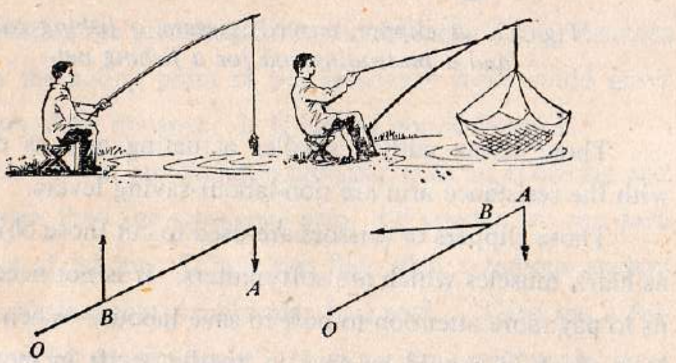

Fig. 24 The forces acting on different points while fishing with a fishing rod or by pulling up the fishing net

The Fulcrum of a Lever

A lever must have a fulcrum. Where should the fulcrum of a lever be located? Is it that the fulcrum must be located between the actuating force and the resistance force? Of course not. Some of the fulcrums are located at one end of the lever. That means, it is located at the same side of these two forces. We design the location of the fulcrum according to the practical use of the device.

The above-mentioned crowbars, scissors, beam balances and seesaws are examples of a lever with its fulcrum located between the actuating force and the resistance force. While choppers, wheelbarrows, tweezers, and the safety valves are examples of a lever with its fulcrum located at one end of the lever (Fig. 25).

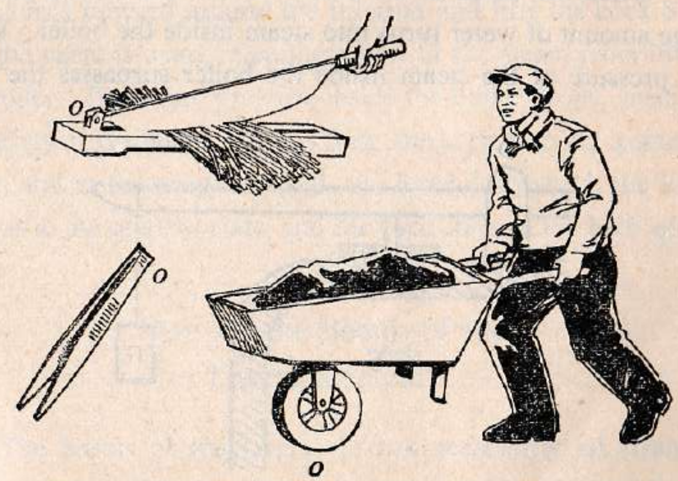

Fig. 25 A chopper, a wheelbarrow and a tweezer.

We want to save labour by using a chopper to cut straw and a wheelbarrow to transport earth. Therefore, their actuating arms must be longer than their resistance arms. That is why we put the resistance force between the actuating force and the fulcrum when designing these devices. They are labour-saving levers.

When using a tweezer to pick up something which is not heavy, we want the instrument to be handy and convenient for use and not necessarily labour-saving. So, the actuating arm should be smaller than the resistance arm. In this case, the actuating force is designed to be put between the resistance force and the fulcrum. They are non-labour-saving levers.

Let's put more emphasis on analysing the lever rule of a safety valve on a boiler. Fig. 26 shows the diagram of a safety valve of a boiler. It is actually a simple automatic regulator.

When the water in the boiler reaches the boiling point, a large amount of water turns into steam inside the boiler. When the pressure of the steam inside the boiler surpasses the pressure-resist capacity of the boiler, the boiler will explode, with an explosion not less powerful than a bomb. It is very dangerous to our lives and property. The safety valve is designed just for the purpose to prevent this kind of accident. It can automatically regulate the steam pressure inside the boiler.

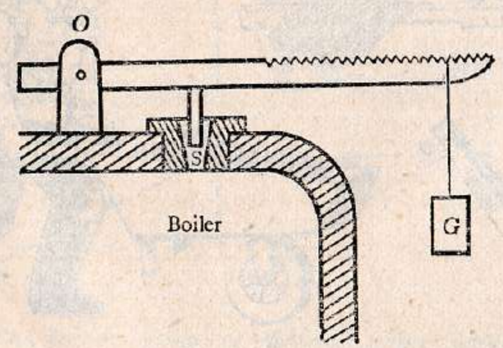

Fig. 26 A diagram showing a safety valve of a boiler

At the top of the boiler, there is a fulcrum installed at one end of the lever, and a weight G is hanging at another end of the lever. A cock S at the steam releasing valve is connected with a rod to the middle of the lever. When the cock fits tightly in the valve, there is no steam escaping out of the boiler.

When the pressure remains under the safety value of the pressure-resist capacity of the boiler, the lever is at rest. That is to say, the cock stays in the hole, and no steam is coming out of the boiler. When the pressure of the steam inside the boiler surpasses the safety value, the cock S receives an upward force from the steam, it upsets the equilibrium of the lever, so the lever turns upward around the fulcrum and lifts the cock S up and the valve is open, releasing a part of the steam from inside the boiler. The steam pressure inside the boiler drops, ensuring the safety of the boiler. At this time, the cock receives a smaller force, and as the weight G pulls the lever downward, the lever returns to the original state, and the cock stays in the hole again.

Are All the Beams of the Levers Straight?

The beams of the levers are not necessarily all straight. For example: The claw hammer used to pull out a nail is not

straight in shape (Fig. 27). The beam of a lever that is not straight in shape is called a bell crank. It is widely used in many places. For example, a springwater pump used in the countryside, a power shovel, a crowbar used for pulling up a rail spike, a self-dumping truck, the pedal plate of a sewing machine, and etc. are all bell crank type levers.

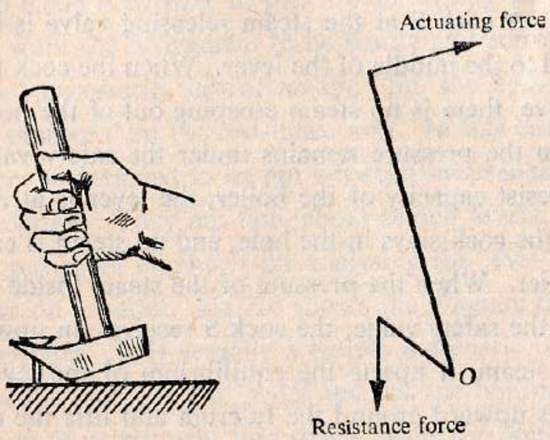

Fig. 27 A claw hammer pulling out a nail

The principle of bell crank is the same as that for a straight lever. Bell cranks can also be divided into labour-saving levers or non-labour-saving levers. A claw hammer pulling up a nail, a crowbar pulling up a rail spike, a self-dumping truck unloading earth, someone pedaling a sewing machine, and a power shovel shovelling earth are all making use of labour-saving levers (Fig. 28).

When studying a bell crank, we must first find out the fulcrum of the device, draw a diagram of the points where the

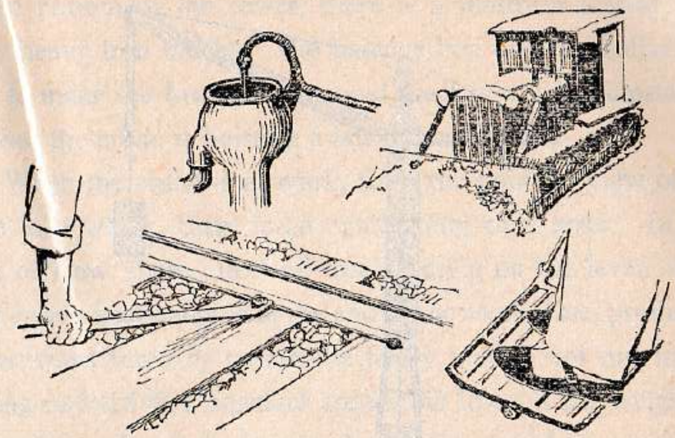

Fig. 28 A spring-water pump, a power shovel and the pedal plate of a sewing machine

forces of the actuating forces or the resistance forces applied and its direction, and then measure the length of the arms carefully according to the definition of the arms. Afterwards, we can write out the equilibrium requirements of the bell crank.

Crane, the Giant Weight-lifter

On a modern construction site, we can't carry on our work without a crane. It can lift up a machine or a heavy load of about a hundred tons or so high up into the air and send it to another place.

Cranes are quite useful in many ways and have many varieties. But they have all developed from the combination of simple mechanisms. In Fig. 29, there is a tower crane towering high in the air with a long beam at the top of the crane. At the

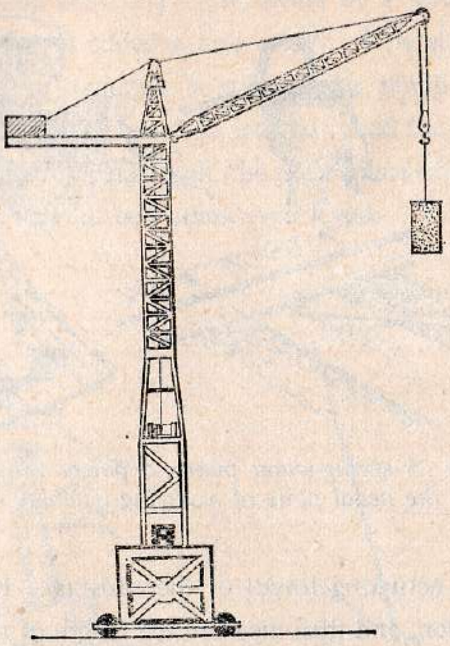

Fig. 29 A tower crane

front end of the beam, there is a pulley. There is a long steel cable wound around the revolving horizontal drum of a winch driven by a motor, with one end of the steel cable passing through the top of the tower, stretching along the horizontal beam to the head pulley, and then hanging perpendicularly downward to a movable pulley. On the movable pulley, there is a hook to be used for hoisting up a heavy load. By operating the electric motor, the steel cable can lift up the heavy load.

On the other side of the crane beam, there is a cantilever beam with a balance box full of heavy metal blocks at the end.

At the bottom of the tower, there is a platform loaded with many heavy iron blocks. The balance box and the ballast are used to make the tower crane stand erect at any circumstances whether the crane is hoisting a heavy load or not.

When the crane is at work, from the point of view of the crane as a whole, there is an equilibrium of a lever. In this point of view, there are three forces acting on the lever. One is the heavy load hanging at the end of the steel cable, producing a downward force F_1 (when the heavy load is not moving or moving upward at a constant speed, the force is the weight of the load), another is the balance box at the end of the cantilever beam, producing a force F_2 (F_2 is the weight of the balance box), and the third one is the gravity force of the earth acting on the crane, producing a force G (G is the weight of the crane itself) (Fig. 30).

When the crane is at work, the functioning fulcrum at this time is at O_1, the equilibrium requirements of the crane is

$$F_1 \times L_1 = G \times L + F_2 \times L_2$$

In this equation, L_1 is the arm of F_1 and L, L_2 are the arms of G and F_2 respectively.

From this equilibrium requirements, we can see that if the crane has not any balance box installed at the end of the cantilever, i.e. $F_2 = 0$, we must build a crane with a self-weight several times greater than the load in order to keep the crane stand erect, because $L_1 \gg L$ and so we must make $G \gg F_1$. To build such kind of a crane is not economical, and at the same time, the crane becomes so clumsy that it can't move freely. The function of the balance box is to keep the crane

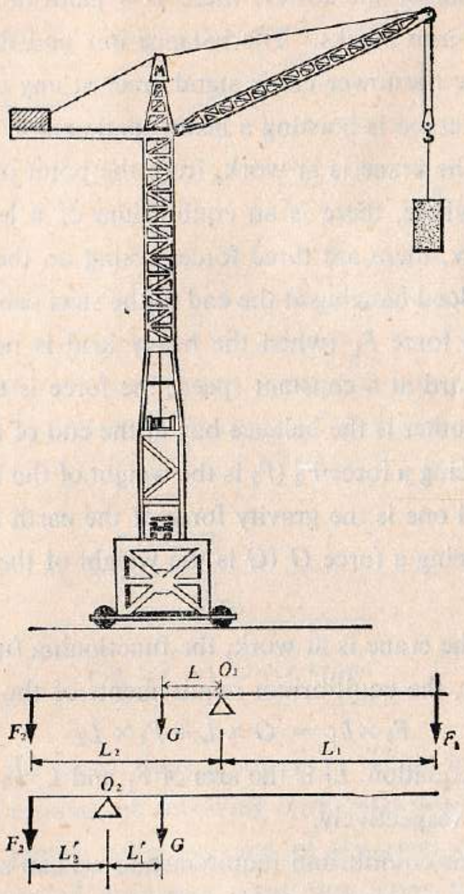

Fig. 30 The analysis of the forces acting on different points when the crane is at work

lighter in weight as well as ensuring the crane to stand erect.

When the crane is not at work, i.e. $F_1 = 0$, is it possible that the balance box may cause the crane to fall backward? The engineers who designed the crane had thought of this problem.

At this time, the center of gravity of the crane changes, so the fulcrum will change from O_1 to O_2. The equilibrium requirements become

$$F_2 \times L'_2 = G \times L'$$

The weight of the crane itself has the function of stabilizing the crane. But due to $L'_2 > L'$, therefore $G > F_2$, i.e. the weight of the crane itself must be heavier than the weight of the balance box.

It is obvious that a crane must be neither too heavy nor too light. So you see, there is much knowledge even in building a crane.

The Lever Is not Always Kept in Balance

The lever equilibrium requirements introduced before is:

Actuating force × actuating arm

= resistance force × resistance arm

and we had pointed out time and again that the lever can not be in balance until the lever at work satisfies the requirements.

In our actual practice, it is true that there are some levers designed for the purpose of seeking balance. But, there are other levers designed for the purpose of seeking imbalance, because these levers are functioning in the state of imbalance.

For instance, when using a crowbar to move a rock, if the crowbar always stays in balance, we cannot move the rock away; or when using a chopper to cut straw, if the chopper always stays in balance, we cannot cut the straw. Then, is there any use of the lever equilibrium requirements in these cases?

Let us try to divide the whole process of cutting straw with a chopper into many, many individual small processes just like the slow motion frames shown in a film. The time spent in every individual small process is very short, and the number of processes is numerous beyond count. We may take any one of these small processes into account and analyse it. In such a process, the lever simultaneously receives actions from the actuating forces and the resistance forces with respective actuating arms and resistance arms. Because the time is too short for a small process, we can assume that its actuating force and resistance force remain constant, and the relation between the forces and the arms satisfies the lever equilibrium requirements. Therefore, it is a short and transient process of equilibrium.

But this process of equilibrium is a temporary one. It cannot stay long. The hand will press the handle of the chopper further down, thus the actuating force changes and the equilibrium requirement of this process is upset. The short and transient process of equilibrium becomes non-equilibrium, it proceeds instantaneously to the next small process.

In the second small process, the actuating force is not the same as the former one. Because the lever turns round the fulcrum, the condition at the point where the chopper meets the straw also changes. The force of action of the straw towards the blade, i.e. the resistance force, also changes accordingly. In the present small process, the new actuating force, resistance force, actuating arm and resistance arm can also be considered as a constant, and at the same time, it satisfies the equilibrium requirements and reaches a new state of equilibrium. The hand continues to press the handle of the chopper downward, and the new equilibrium is upset again and thus it proceeds to the third small process and reaches another new state of equilibrium. In such a way, the lever proceeds from equilibrium to non-equilibrium and to another new equilibrium and so on and so on until the straw is cut. This alternative gradual changing process from equilibrium to non-equilibrium of a lever shows that the equilibrium state of a lever is temporary and relative, and the non-equilibrium state of a lever is absolute.

Yet, the equilibrium process of a lever runs through the whole working process. If there is no equilibrium process, there will be no non-equilibrium process.

The lever equilibrium requirement is a very important problem in analysing the non-equilibrium state of a lever.

CHAPTER III

PULLEYS — A VARIANT OF LEVERS

Pulleys are usually seen on all kinds of cranes. When we are using a pulley, the direction of the force applied can be changed. It will be easier and more convenient for us to do the job. By using pulleys, a lot of labour can be saved, too.

Pulleys of today are usually made with a grooved wheel fixed on a shaft in a frame (Fig. 31). It can turn freely around the shaft. This kind of pulley is quite strong and light, easy to carry and quite durable in use. Therefore, it can be widely used in our daily work.

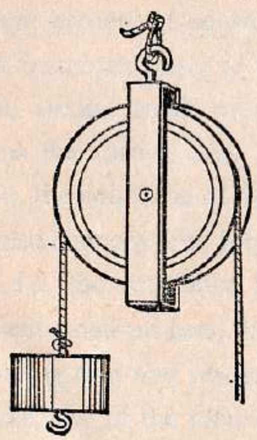

Fig. 31 A pulley

Although the wheel of the pulley is round in shape, it is still a kind of lever from the point of view of its working principle. It is a variant of a lever. That is to say, it is a round-shaped lever.

From the point of view of its usage, it can be divided into two categories: a fixed pulley or a movable pulley. A pulley block is the combination of some simple fixed pulleys and movable pulleys, quite easy to use and has different usages. After we have analysed thoroughly the working principles of the fixed and movable pulleys one by one, it will be easy to understand clearly the assembling of the pulley blocks and their applications.

Fixed Pulleys — Equal-Arm Levers

If the revolving shaft of a pulley remains in the same position when the pulley is at work, this kind of pulley is called *fixed pulley.* (Fig. 32)

It is quite obvious that the fixed pulley can change the direction of the hoisting force applied. But, is the fixed pulley labour-saving? The following experiment will give the answer.

Hang a weight at one side of the fixed pulley. Another weight of same weight should be hung at the other side of the fixed pulley so that the pulley will keep in balance (Fig. 33). If the weight of the weights at the two sides does not equal to each other, the pulley will rotate speedily causing the heavy weight to drop downward and the light weight to go upward. Thus the equilibrium of the pulley is upset.

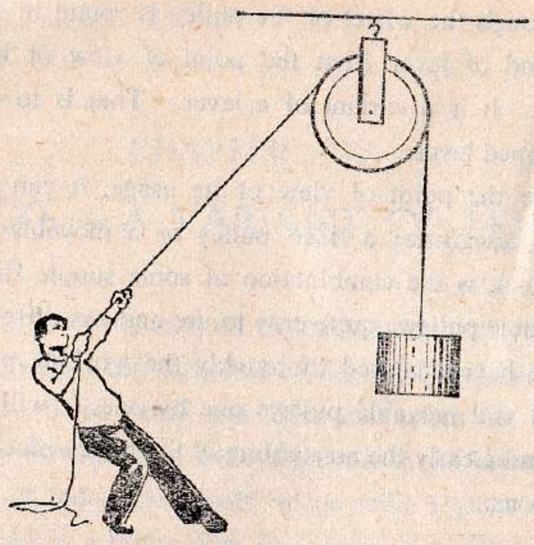

Fig. 32 A fixed pulley at work

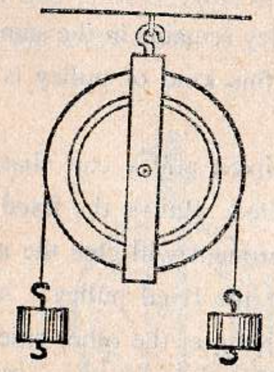

Fig. 33 Two weights of equal weight keep the balance at rest

We came to the conclusion that the only way to make the fixed pulley keep in balance is to let the weight hanging at the two sides be equal to each other.

When we want to lift a load upward by using a fixed pulley, we have to pull the rope downward. Now, let us measure the pulling force of the hand by using a spring balance (*a* in Fig. 34). If we can control the pulling force by our hands so that the load will rise at a constant speed, we will discover that the reading on the spring balance is equal to the weight of the load. That is to say, pulling a load upward at a constant speed by using a fixed pulley, the pulling force is equal to the load. When the direction of the pulling force changes, for instance, pulling diagonally, pulling horizontally, and pulling vertically, the force would be the same (*b* in Fig. 34).

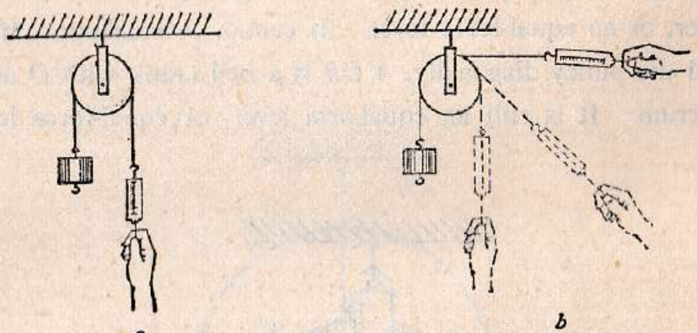

Fig. 34 An experiment of pulling a load upward

We may draw the same conclusion for the above two experiments. Using a fixed pulley to lift up a load can only change the direction of the force applied, but it cannot save labour, i.e. the force we use to lift up a load without a pulley is equal to the weight of the load.

Why can't we save labour by using a fixed pulley? Because it must obey the lever rule.

Let's imagine the case as shown in Fig. 35 that a fixed pulley is composed of many rods equal in length with shaft O as the fulcrum. When we pull the rope vertically downward at a constant speed, rod AB is at a horizontal position. The weight of the load acting on the rope and the force applied by the hand acting on the opposite rope hanging respectively from both ends of the rod are the same. When any one of the rods that composed the pulley reaches the horizontal position, the force acting on it will be the same. The radii of the pulley at any point are the same, therefore $OA = OB$, i.e. the actuating arm is equal to the resistance arm. According to the lever equilibrium requirements, the fixed pulley is an equal-arm lever, or an equal-force lever. It cannot save labour. If we pull the pulley diagonally, $A'OB$ is a bell crank with O as its fulcrum. It is still an equal-arm lever, or equal-force lever.

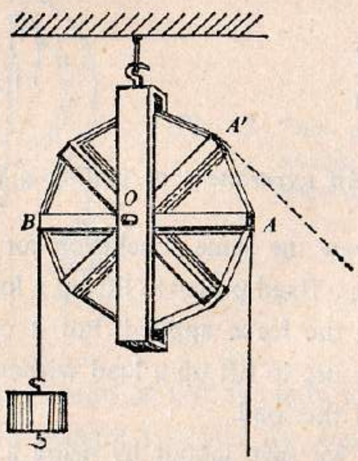

Fig. 35 The lever rule of a fixed pulley

Fig. 36 shows the diagram of the acting forces of an equal-force lever of a fixed pulley.

A fixed pulley does not save labour, and at the same time, it does not spend more labour. But it can change the direction of the force applied. This characteristic is quite useful in our practical work. It is always used to lift those objects not too heavy, as it is handy and convenient. The fixed pulley at the top of a flagpole enables us to hoist a flag up without risking the danger by climbing up the flagpole. A fixed pulley at the top of a mast on a ship enables the men to pull the rope downward and the sail will go up (Fig. 37). The fixed pulley installed on a tower crane is also used to change the direction of the force applied.

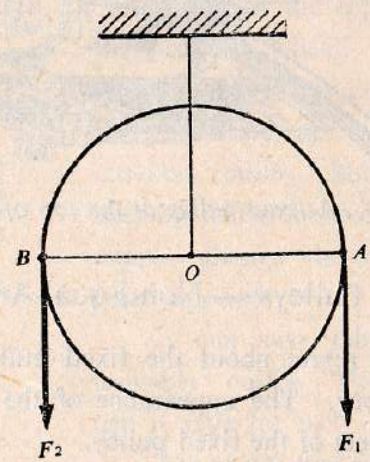

Fig. 36 A diagram showing the acting forces of an equal-force lever of a fixed pulley

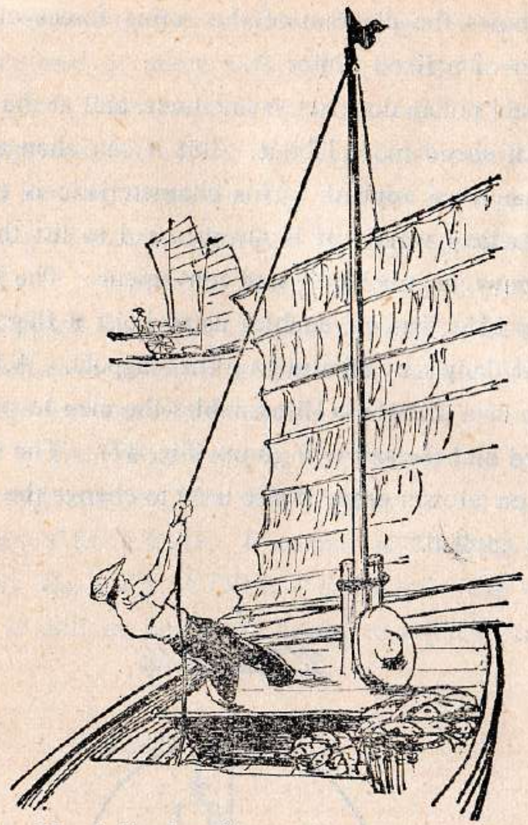

Fig. 37 *A fixed pulley at the top of a mast*

Movable Pulleys — Non-Equal-Arm Levers

People feel regret about the fixed pulleys because they cannot save labour. The appearance of the movable pulleys remedied the defect of the fixed pulley.

The outer appearance of a movable pulley looks the same as the fixed pulley. But when at work, the revolving shaft moves along with the load (Fig. 38).

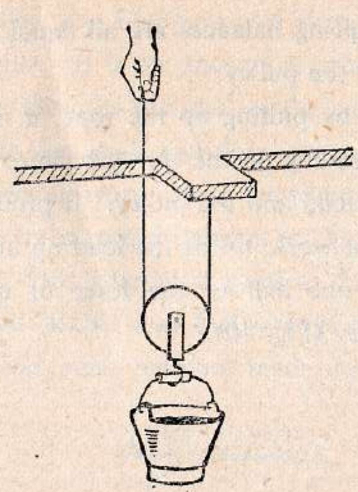

Fig. 38 *Lifting water by using a movable pulley*

When the movable pulley is being used, one end of the rope should be fixed at a point, the load is hanging under the movable pulley, and the other end of the rope passing round the grooved wheel. The hand will pull the rope upward and the load will be lifted up together with the movable pulley. But, it is obvious that by using the movable pulley we cannot change the direction of the force applied.

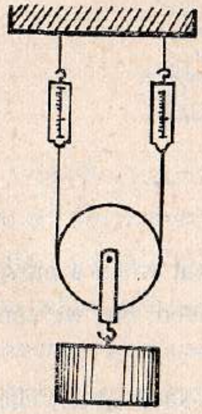

Fig. 39 *By using two ropes to lift up a load*

It can save labour by using a movable pulley. How much force can it save for us?

Try to use two spring balances to be attached to the movable pulley (Fig. 39). Lift up the load and let it remain there at rest. We can

discover the readings on both spring balances are all equal to half the weight of the load and the pulley.

When we lift up the load by pulling up the rope, if the speed is kept in constant, the reading on the spring balance is also a half of the weight of the load and the pulley. It proves that when a movable pulley is at work, to lift the load up at a constant speed, we need only one half of the force of the weight of the load and the pulley (Fig. 40).

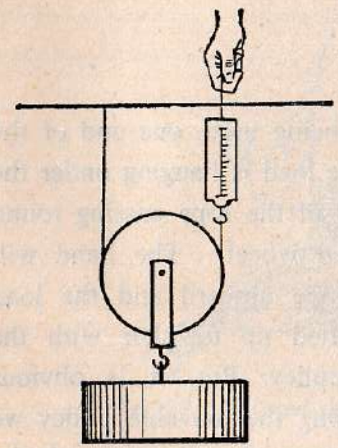

Fig. 40 Use a spring balance to measure the pulling force by the hand

The above two experiments showed that when a movable pulley is used, half of the labour can be saved, but we cannot change its direction of the force applied.

The reason why a movable pulley can save labour should also be explained from its working principle.

The essential reason for the labour-saving of a movable

pulley was obtained also from the lever equilibrium requirements. It is an unequal-arm lever.

Because the shaft of the movable pulley moves up together with the load, therefore it is not the fulcrum of the movable pulley at work. Now the fulcrum is located at point O' where the fixed rope is tangent to the curved edge of the wheel (Fig. 41). This fulcrum changes as the load is being lifted up. Maybe some people may feel strange about it. But it is not so complicate when we have made the point clear.

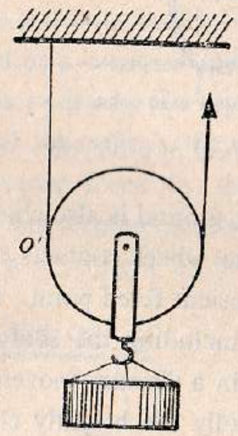

Fig. 41 The fulcrum of a movable pulley

What is a fulcrum? A fulcrum is the fixed point of a lever. If we set the rear-wheel of a bicycle on a support and make it run, the shaft of the wheel is a fixed point and any other points of the wheel are turning around the fixed point in a circular movement. The speed of the fixed point is zero. When the bicycle is running on the road, the rear axle will also move forward. Its speed is the speed of the running bicycle and is not equal to zero, then the rear axle is not the fulcrum. At

this transient moment, the point where the wheel touches the ground is the fixed point, and the speed of this fixed point is equal to zero (Fig. 42). The wheel is rolling forward, the

Fig. 42 The free-wheel of a bicycle

point where the wheel contacts the ground is also changing from time to time. The point that the wheel contacts the ground at the transient moment is the transient fixed point. At this moment, every point of the wheel including the shaft is turning around this transient fixed point in a circular movement at different radii. If you notice carefully the brightly electroplated spokes of the rear-wheel, as the bicycle is running at a constant speed, the upper half of the spokes of the wheel shine like a sparkling half circular disc, one is unable to distinguish one spoke from the other, while the lower part of the spokes can be clearly seen one by one. This is because the spokes in the upper part of the wheel are located farther away from the fixed point with a high running speed and the spokes in the lower part of the wheel are located quite near the fixed point with a slower running speed.

For the same reason, when the movable pulley is hoisted up, we can imagine that it is moving along the fixed rope in an upward direction. The point where the rope is tangent to the edge of the wheel is the transient fixed point. It is obvious that when the movable pulley is at work, every point on the fixed rope is a transient fulcrum whenever it is tangent to the edge of the wheel. The fulcrum of the movable pulley is changing from time to time. But, no matter how it changes, the fulcrum is always on the fixed rope that hangs the pulley.

Let's assume that at a certain transient moment, the fulcrum of the movable pulley is O' (Fig. 43). The force applied by the hand at a constant speed is F_1 (F_1 is equal to the force acted on the pulley by the rope), the actuating arm is $2R$ (R is the radius of the pulley), the weight of the load and the pulley is the resistance force F_2, (Sometimes, for the sake of convenience of our explanation, we can assume that the weight of the pulley is very light so it can be neglected, and only the

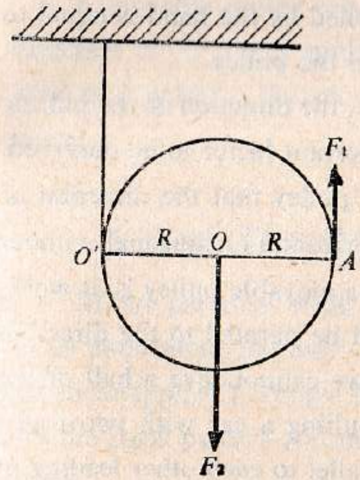

Fig. 43 A diagram to show the lever principle of a movable pulley

weight of the load should be considered. In actual practice, the difference is very small.) and the resistance arm is R. According to the lever equilibrium requirements, the equation can be written as follows:

$$F_1 \times 2R = F_2 \times R$$

and thus

$$F_1 = \frac{1}{2}F_2$$

Fig. 43 is a diagram showing the lever rule of a movable pulley. From this we can see that the movable pulley is a transient unequal-arm lever with its fulcrum at one end of the lever. The actuating arm is two times that of the resistance arm, so it is possible to save half of the labour. The movable pulley is a labour-saving lever.

We can think in this way that the weight of the load is shared equally by the two ropes, so each rope takes up half the weight. The hand that pulls the rope applied a force that equals to the force acted on the rope by the load. Therefore, when we use a movable pulley, the force applied by the hand is equal to a half of the weight of the load and the pulley.

When we use a movable pulley, the direction of the pulling force applied by the hand is an important factor to be observed. It is not the same as using a fixed pulley that the direction of the pulling force can be vertical, horizontal or diagonal without changing the force applied. When a movable pulley is at work, the hand that pulls the rope should be parallel to the direction of the resistance force, otherwise, we cannot save a half of the weight. It is just like two men pulling a car with two ropes (Fig. 44). If the two ropes are parallel to each other leading in

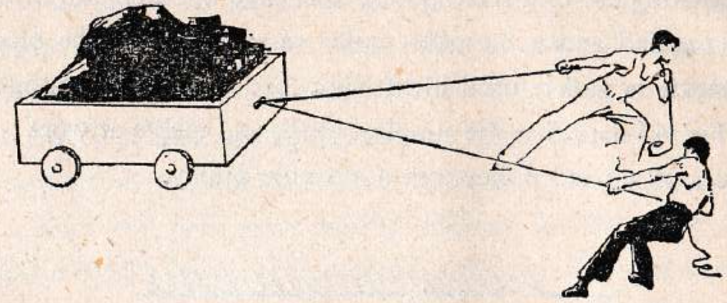

Fig. 44 Two men pulling a car

front of the car, it is a labour-saving way to pull the car. If these two ropes are pulling in different directions forming an angle between them, it will not save labour. The greater the angle between these two ropes is, the more the force will be. If the angle between these ropes is 180° and the forces applied to the ropes are of the same magnitude, the car cannot move forward but stay at the same place.

A movable pulley can save labour but cannot change the direction of the forces applied. It is inconvenient in using such kind of a pulley. Therefore, we seldom use a movable pulley alone.

A Block That Overcomes the Drawbacks

In our practical work, we want to save labour as well as to be convenient for use. (That is to change the direction of the force applied.) People invented a system of pulleys combining the fixed pulleys and movable pulleys to form a block and tackle.

Making use of a fixed pulley to change the direction of the force applied and a movable pulley to save labour, the block and tackle is widely used in lifting a load or pulling a weight.

Fig. 45 describes the simplest block and tackle at work. It consists of a fixed pulley and a movable pulley.

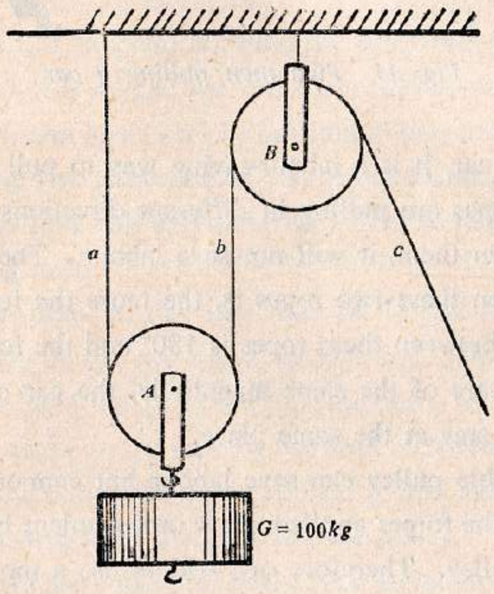

Fig. 45 A simple set of pulleys

If we just neglect the weight of the movable pulley and the rope used as well as the friction between the pulley and the rope, and at the same time, the rope cannot be elongated, let us calculate the force to be used to pull up a 100-kilogram load at a constant speed.

First, let us study the principle. The movable pulley *A* can

save half the force required, so rope *b* needs only to bear 50 kilograms of weight. The fixed pulley *B* can only change the direction of the force applied, so the force acted on rope *c* is only 50 kg without saving any labour. Therefore, the hand that is pulling the rope bears a force of 50 kg.

Then we can use a spring balance to check the force applied by the hand. The reading is 50 kg. It shows that the experiment proves the analysing of the principle correct.

This kind of simple system of pulleys can save half of the labour and can also change the direction of the force applied, so it is easy and convenient for use.

In order that we want to save more labour as well as to change the direction of the force applied, we usually put a number of fixed pulleys and movable pulleys to form a combined system of pulleys called a block and tackle. Fig. 46 shows two sets of block and tackle. They are all developed from the simple ones.

In Fig. 46 *a*, the block is formed by three fixed pulleys and three movable pulleys connected together to lift a load. There are so many ropes connected to the pulleys. It would be a painstaking job to analyse the force acting on each rope. The simplest way is to count the number of the ropes connected to the pulleys that bear the weight of the load and the pulleys. When the load is raised at a constant speed, each rope bears only a part of the weight. Now, there are six ropes that connected to the load and the movable pulleys. So, each rope bears only one sixth of the total weight of the load and the pulleys. The fixed pulleys hanging at the top of the beam do not save labour. The ropes that

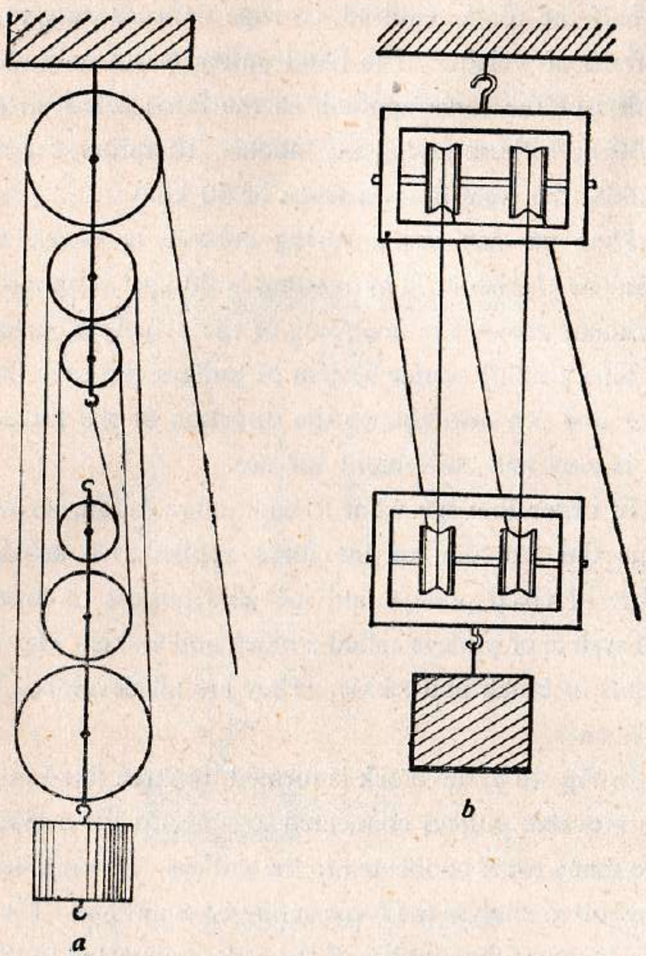

Fig. 46 Two sets of more complicated system of pulleys

connected on the both sides of the fixed pulleys bear equal force. Therefore, we can conclude that the force applied by the hand is one sixth of the weight of the load and the movable pulleys.

Hence, when we are going to determine how much labour can be saved by a certain kind of block, we can just do according to the aforesaid way to count the number of the ropes that connected to the load and the movable pulleys so that we can calculate the force applied by the hand to be equal to 1/n.

The system of pulleys shown in Fig. 46 *a* is quite simple in analysing the pulling forces. But in practical use, it is not widely used because there is a shaft for each pulley and, at the same time, it needs a lot of space and is rather inconvenient to carry and install.

The block and tackle shown in Fig. 46 *b* has more practical value. It needs smaller space and there is only one shaft for the movable pulleys or the fixed pulleys. It can be skilfully constructed and strong, and is convenient to carry and install.

It is quite obvious that the block in Fig. 46 *b* needs a pulling force of one fourth of the weight of the load and the movable pulleys so as to lift it up at a constant speed.

Such kind of a block can be used to pull a load as well as to lift up a load in a labour-saving way (Fig. 47). While we are pulling a load at a constant speed, the resistance force is not the weight of the load. It is the friction force between the load and the ground. When we want to determine the pulling force, we must first count the number of ropes connected

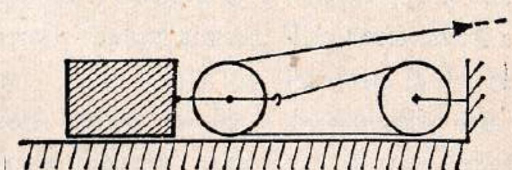

Fig. 47 To pull a load by using a block

to the load and the movable pulleys, and then divide the friction force by the number of ropes so as to get the required pulling force to pull the load at a constant speed.

The characteristics of labour-saving and direction-changing of a block and tackle are quite attractive. Is it better to install more movable pulleys? The more the better? Of course not. Although it is possible to save labour, it will increase the weight of the movable pulleys and the friction forces between the wheels and the shaft and between the ropes and the wheels. Moreover, we have to pull down quite a long rope in order to lift up a load only a little height. This is the same reason as the use of too long a lever is not practical. We will answer this question later on in Chapter V "*Mechanical Work and Its Principle*".

So, the actual conditions must be taken into consideration as a whole when choosing a proper type of block for a specific job. A comprehensive study should be made to the problems of labour-saving, convenience, and using a shorter rope to lift up the load higher, etc.

CHAPTER IV

WHEEL AND AXLE—ANOTHER VARIANT OF LEVERS

When using a straight lever to draw water from a well with a bucket, we will find that the bucket cannot go very deep into the well because the turning angle of the lever is rather small. If the water in the well is not deep, we can use such a straight lever to draw water. If the water is too deep, it will be hard for a simple lever to do the work. If we make some change of the lever by making it turn in a continuous way, that is, the actuating arm and the resistance arm are all turning around the fulcrum continuously, and letting the rope wind around a revolving drum, the height for the bucket to draw water from the well will be greatly increased. The waterwheel used in the countryside for drawing water is an example of such kind of a lever (Fig. 48).

A waterwheel consists of a wooden drum (called the axle) and a big handle (called wheel). The drum and the handle have the same axis. The radius for the drum is the resistance arm and the radius for the handle is the actuating arm. Their common axis is the fulcrum. The force acting on the drum by the rope that hangs the bucket is resistance force; while the force applied by the hand on the handle is actuating force.

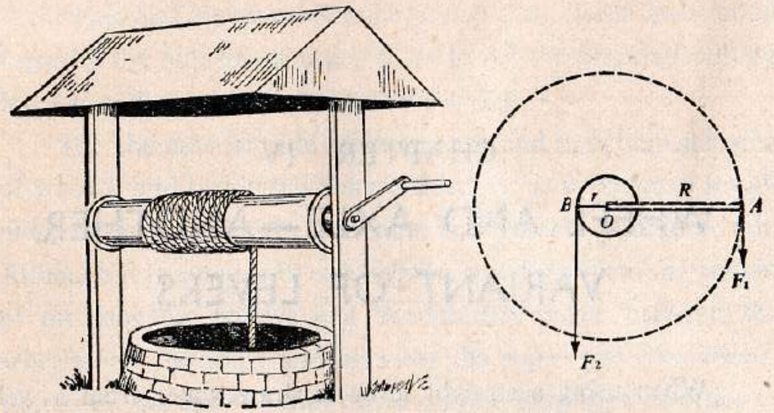

Fig. 48 A diagram showing a waterwheel and the forces acting on it

Those appliances consist of a *wheel* and an *axle* like a waterwheel and revolving around a common axis are called wheel and axle.

The Lever Rule of the Wheel and Axle

Wheel and axle is a kind of lever which can rotate continuously.

Actuating force F_1 acting on the *wheel's* edge of a wheel and axle is tangent to the *wheel* (Fig. 49). The actuating arm is the radius R of the *wheel*. The resistance force F_2 is also tangent to the *axle* with a downward acting force on the edge of the *axle*. The resistance arm is the radius r of the *axle*. When the *axle* rotates at a constant speed, the wheel and axle is in a state of equilibrium. According to the lever rule, we can write out the equation as follows:

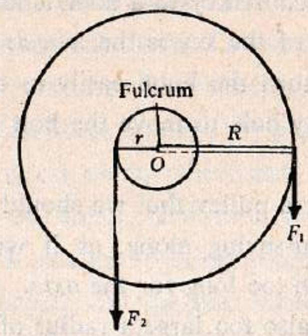

Fig. 49 The lever rule of the wheel and axle

$$F_1 \times R = F_2 \times r$$

and thus

$$F_1 = \frac{r}{R} \times F_2$$

This equation shows that if the radius of the *wheel* is n times that of the *axle*, the actuating force acting on the *wheel* is 1/n times the resistance force acting on the *axle*. It is obvious that making use of a wheel and axle can save labour. When using a wheel and axle to lift a load from a deep well, we need not apply an upward force. We only require the direction of the actuating force to be able to turn the *wheel* around the axis. So, the use of the wheel and axle can save labour as well as change the direction of the force applied.

The switch on a TV set or a tape recorder is also a kind of wheel and axle. The knob of the switch is the *wheel*; and the metal shaft fixed to the knob is the *axle*. We can just apply a little force to turn the knob so as to rotate the metal shaft in order to turn on or off a TV set or a radio set. A door handle is also a wheel and axle. The knob is the *wheel* and the shaft

connected to the handle is the *axle*. A key to a door is also a kind of wheel and axle. The bow of the key is the *wheel*; and the plug is the *axle*. So, we can turn the knob easily to open the door or turn the key in the key hole to move the bolt of a lock.

It is the same with a lever or a pulley that we should not pay too much attention to labour-saving alone, as it would make the radius of the *wheel* much too long for the *axle*. It is not only inconvenient to use, but also too large a radius of the *wheel* which will turn a big circle while the *axle* will only turn a very small circle. So when we lift up a load, the load will rise only a little height that equals the length of the circumference of the small circle. It is not economical for us to do a thing like this.

The Multi-function of Wheel and Axle on a Bicycle

Bicycles are widely used for communication. It has quite a lot of wheels and axles. The wheel and axle play a great role on a bicycle (Fig. 50).

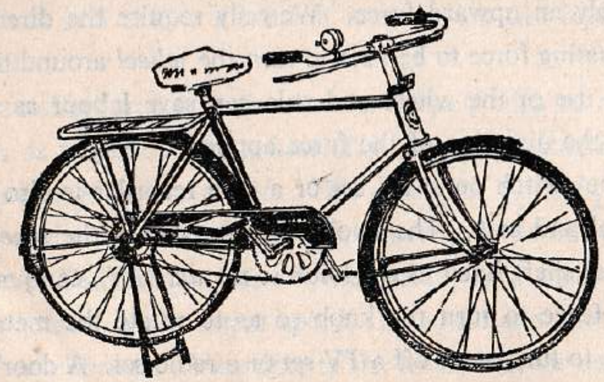

Fig. 50 The wheel and axle on a bicycle

The chain wheel at the bottom bracket bearing axle and the two pedals formed a wheel and axle. The pedals form the *wheel*; and the chain wheel is the *axle*. We can pedal the pedals with less force to make the pedals turning around the axle, thus making the chain wheel also turning around the axle so as to drive the chain. This is a labour-saving wheel and axle.

A smaller sprocket wheel (flywheel) on the rear axle of the bicycle and the rear wheel formed a wheel and axle too. The small sprocket wheel is the *wheel*; and the rear wheel is the *axle*. This is a non-labour-saving wheel and axle. When the chain fits tightly to the small sprocket wheel and drives the wheel so that the rear wheel will also be driven in the same direction. The small wheel turns a circle and so the rear wheel will also turn a circle. The distance of the bicycle moving forward is equal to the length of the circumference of the rear wheel.

The handlebar and the front forks formed another wheel and axle. The handlebar is the *wheel*; and the front forks are the *axle*. When we want the bicycle to turn to the left or right, we can just turn the handlebar slightly and the front forks will turn the wheel to the left or right. This is a labour-saving wheel and axle.

The handle of a brake and the brake lever on the other end formed a wheel and axle. The handle of the brake is the *wheel;* and the brake lever on the other end is the *axle*. Press the brake handle, thus pulling up the brake lever to make the brake work. This is a labour-saving wheel and axle.

The bicycle saddle and the seat pillar connected to it form-

ed a wheel and axle. The saddle is the *wheel*; and the seat pillar is the *axle*. If the saddle is not in correct position, we can just turn it by hands and the pillar will be turned and the saddle adjusted. This is also a labour-saving lever.

There are two sets of wheel and axle in the bicycle bell. The small handle of the bell drives a wheel axle, and this wheel axle drives another wheel axle to ring the bell. In order to ring the bell several times in a short time, these two sets of wheel and axle are all non-labour-saving wheel and axle in design.

CHAPTER V

MECHANICAL WORK AND ITS PRINCIPLE

In our daily life, people may say that someone *has done a work* or *has done a job*, including all kinds of mental and manual labour. When we are examining the movement of all kinds of mechanisms and machines, we may discover that in the process of their work, there exists a certain kind of force and a displacement due to the action of the force. This phenomena is quite important. In physics, we express this phenomena as a concept of *work* in all kinds of job done by the mechanisms and machines. In order to make a train move, we have to use a locomotive to apply a pulling force to the train. In the direction of the pulling force, the train moves a certain distance. In this case, we say the locomotive has done a work on the train. When a work is done on the train by the locomotive, the train changes from the state of static to dynamic. The mode of motion has changed. So, there is a close relation between the work done and the change of the mode of motion of the object. The study of *work* in physics is very important.

The concept of *work* in physics is entirely different from

actually *doing a work* in our daily life. The concept of *work* in physics is definite, precise, and specific.

What is work? Work is defined in physics as follows: The work done on a body by a force exerted on the body is equal to the force exerted on the body times the displacement of the body in the line of force.

Let F be the force exerted on a body, S be the distance displaced in the line of force F, and W be the work done as the body moves a distance of S under the force F applied to the body. The equation can be written as follows:

$$W = F \times S$$

The actuating forces acting on the levers, pulleys and wheels and axles make them move a certain distance in the line of force. The work done by the actuating force is equal to the actuating force times the distance of displacement. It is thus called work of actuating force. The resistance force also makes the lever or pulley or wheel and axle move a certain distance of displacement in the line of resistance force. The product of the resistance force and the distance of displacement is called work of resistance. Sometimes, the direction of motion of the mechanism is just opposite to the direction of the resistance force, so the resistance force is doing a negative work. We usually say that the mechanism overcomes the resistance force to accomplish a work.

It is quite obvious that all mechanisms are used to do a work. Now let us study respectively the work of the actuating force and the work of resistance force of a lever, a pulley and a wheel and axle so as to find out the laws.

The Work of Actuating Force of a Lever Is Equal to the Work Done to Overcome the Resistance Force

Fig. 51 shows the work performed by a lever. Force F_1 is the actuating force, F_2 is the resistance force (usually, it is the same as the weight of the load). Owing to the fact that the actuating arm is longer than the resistance arm, this is a labour-saving lever. If F_1 makes the lever rotate at a constant speed, one end A of the lever is moving along the curved line around the fulcrum O, and the other end B is also moving along a smaller curved line around the fulcrum. Let's assume that the lever is working in a process from equilibrium to unequilibrium and then to equilibrium and unequilibrium alternatively. In a transient moment of equilibrium process, the distance of motion at A and B is equal to the curved length of S_1 and S_2 respectively. Because the numerical values of S_1 and S_2 are very small, we can put it approximately as $S_1 = AC$ and $S_2 = BD$. Because the direction of motion at point A is approximately

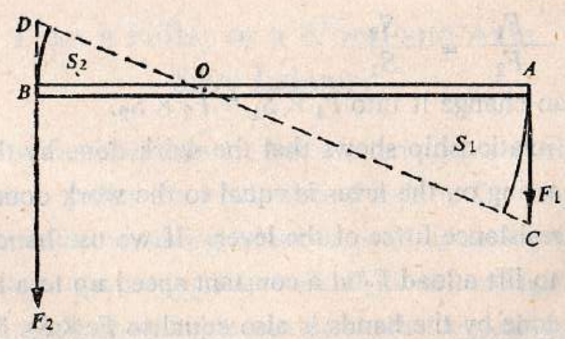

Fig. 51 Showing the work performed by a lever

the same as the direction of the actuating force, the work of actuating force is $F_1 \times S_1$; and the direction of motion at point B approximately opposite to the resistance force. At this time, the resistance force is performing a negative work, i.e. the lever overcomes the resistance force to perform a work. Thus $F_2 \times S_2$ is the work done.

The equilibrium of the lever in this transient moment follows the equilibrium requirements, i.e.

$$F_1 \times OA = F_2 \times OB$$

or it can be written as follows: $\dfrac{F_1}{F_2} = \dfrac{OB}{OA}$

From Fig. 51, we can see that in $\triangle AOC$ and $\triangle BOD$, the three angles of these two triangles are equal respectively. Therefore, $\triangle AOC$ and $\triangle BOD$ are similar. The ratio between the sides opposite to each angle of these two similar triangles are equal, too.

Thus $\dfrac{OB}{OA} = \dfrac{BD}{AC} = \dfrac{S_2}{S_1}$

We can compare this equation with the former one, thus we can obtain

$$\frac{F_1}{F_2} = \frac{S_2}{S_1}$$

and we can change it into $F_1 \times S_1 = F_2 \times S_2$.

This relationship shows that the work done by the actuating force acting on the lever is equal to the work done to overcome the resistance force of the lever. If we use hands instead of a lever to lift a load F_2 at a constant speed up to a height S_2, the work done by the hands is also equal to $F_2 \times S_2$. That is to say, the work done by the hands is the same as the work done

by the actuating force acting on the lever. To discuss the lever from the point of view of work done the lever cannot save any labour. This law is called the principle of work of a lever. Its equation is

$$F_1 \times S_1 = F_2 \times S_2$$

From this equation, we can see that the work done by the actuating force cannot save any labour. As for $F_1 \times S_1$, the product is fixed. Therefore, when we are using a lever, we cannot seek only labour-saving, as the smaller the force F_1 becomes, the longer the length of the actuating arm will be as compared with the resistance arm. From Fig. 51, we can see that the longer the length of the actuating arm is, the longer the travel distance of the point along the direction of the actuating force applied will be. Although we have saved a lot of labour, we have to go a longer distance so that we have to spend more time in doing the job. It is not economical. So, when we use a lever, we have to consider the matter of labour-saving carefully, or it may not be beneficial.

Does a Pulley or a Wheel and Axle Save Labour?

A lever can save labour, but it cannot save work. Then, what about a pulley or a wheel and axle? Do they have a special capability of saving labour as well as saving work?

The laws concerning the work of the actuating force of a pulley and a wheel and axle can be studied by using the same analysis for the lever.

Let F_1 and F_2 be the actuating force and the resistance force respectively acting on a fixed pulley as shown in Fig. 52. AO and BO are the actuating arm and the resistance arm respectively. The equilibrium requirements of a fixed pulley are as follows:

$$F_1 \times AO = F_2 \times BO$$

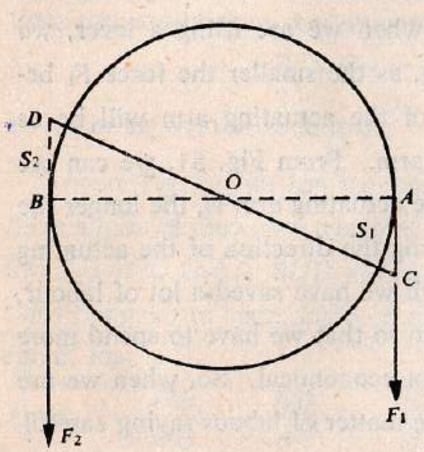

Fig. 52 Showing the working condition of a fixed pulley

Approximately we can consider that $S_1 = AC$, $S_2 = BD$ and ΔAOC and ΔBOD are similar. Finally, we can write out the equation as follows:

$$F_1 \times S_1 = F_2 \times S_2$$

This relationship shows that it cannot save work by using a fixed pulley because the work done by the actuating force must be equal to the work of resistance overcome by the pulley. It is the same as the work done by lifting a load F_2 to a height S_2. Therefore, we cannot save any work. This is the mechanical work principle of a fixed pulley.

Then, let us study the mechanical work principle of a movable pulley.

Fig. 53 shows that a movable pulley is lifting up a load weighing G. According to the analysis in the former chapters, we know that to lift up the load at a constant speed, the pulling force needed is only one half of the load G. We can measure the length by using a scaled ruler. When the load is raised to a height h, the distance required for the rope to travel is $2h$. Hence, the work done by the actuating force is

$$\tfrac{1}{2}G \times 2h = Gh.$$

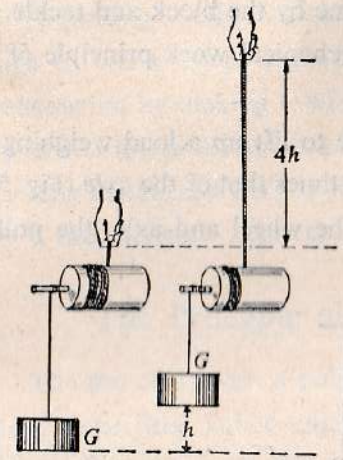

Fig. 53 Length of rope needed to lift up a load by a movable pulley

The work done to overcome the resistance force by the pulley is also equal to Gh. Therefore, when we use a movable pulley, the work done by the actuating force is also equal to the work of resistance overcome by the pulley. From the point of view of the work done, we cannot save labour no matter whether we use a movable pulley or not. This is the mechanical work principle of a movable pulley.

From this work principle of a movable pulley, it is clear that the movable pulley cannot save any work, but it can save half the force used, therefore, it is necessary to apply an actuating force to pull a distance twice the height of the load being lifted up.

As for a block and tackle, the principle is the same. If a block and tackle can use only one tenth of the actuating force, we have to pull the rope ten metres in order to lift up a load only one metre high. It does not save any work done by the pulling force. The work done by the pulling force is equal to the work of resistance overcome by the block and tackle.

Finally, let us study the mechanical work principle of the wheel and axle.

Let us use a wheel and axle to lift up a load weighing G, with the radius of the *wheel* four times that of the *axle* (Fig. 54). From the working principle of the wheel and axle, the pulling

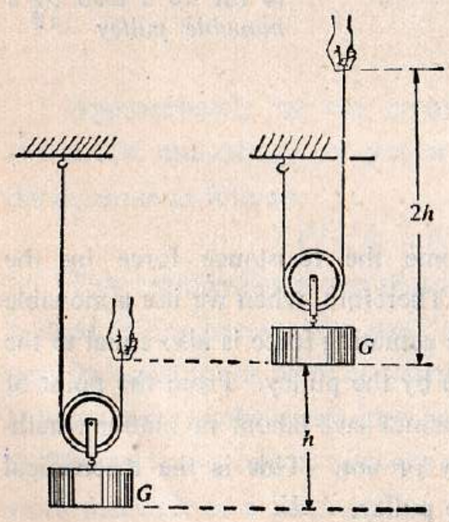

Fig. 54 An experiment of the mechanical work of a wheel and axle

force needed is $\frac{1}{4} G$. We can measure it with a ruler. When a load is raised to a height h, the length of the rope pulled upward is equal to $4h$. At this time, the work done by the pulling force to the wheel and axle is as follows:

$$\frac{1}{4}G \times 4h = Gh$$

The work of resistance overcome by the wheel and axle and the work done by lifting up a load are all equal to Gh. This shows that it cannot save any work done by using the wheel and axle. This is the mechanical work principle of the wheel and axle.

According to these facts, we understand that when we design or use a wheel and axle, we cannot merely seek after labour-saving by making a wheel with a very large radius. It may save a lot of labour, but the actuating force must travel a very long distance while the load hanging on the axle is raised only a little height. This is not economical.

The Principle of Mechanical Work

The use of a lever, a pulley or a wheel and axle is labour-saving some time, other time it is time-saving by travelling a shorter distance, and still other time it just changes the direction of the force applied. However, all of them cannot save any work. The work done by the actuating force towards them are all the same as the work done by hand or by mechanism.

People have done many experiments on all kinds of mechanism and discovered the laws concerning the mechanical work. It is observed not only by those simple mechanisms,

such as lever, pulley or wheel and axle, but by other simple mechanisms as well, such as inclined plane, screw, etc., and also complicated machines composed of these simple mechanisms. This law is called the mechanical work principle. It is stated as follows: When people are making use of any mechanisms, the work done by them is the same as the work done by using their own hands directly. That is to say, we cannot save any work by using any kind of mechanism.

It was through a very long period of practice and study that human being learned and defined the object law of the mechanical work principle finally in the 18th century. This very important law is recognized and accepted. With a thorough understanding of this law, we no longer waste our time and energy to design those work-saving machines. Furthermore, we can learn and calculate some of the problems of a machine by utilizing this law.

The Application of the Mechanical Work Principle in Mechanisms

Here, we are going to introduce a kind of widely used pulley with simple structure and good labour-saving characteristic — the differential pulley.

The differential pulley (Fig. 55) consists of two fixed pulleys with about the same diameters installed on a common shaft and one movable pulley with a smaller diameter. The two fixed pulleys above and the small movable pulley below are connected with a closed block chain. There are teeth in the

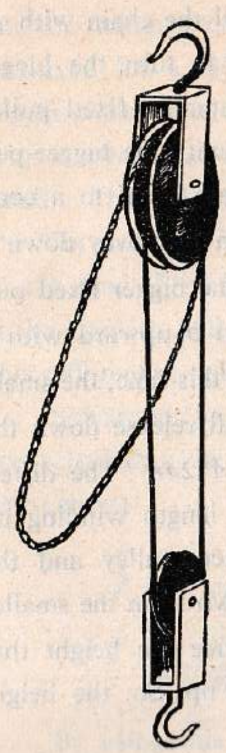

Fig. 55 A differential pulley

grooves, so it will not slip as the chain is meshed with the teeth.

The way to wind the block chain around these pulleys is quite unique. First, the chain winds round the fixed pulley with a smaller diameter, and then stretches down to wind round the slightly smaller movable pulley, and goes upward to wind round the fixed pulley with a bigger diameter, and finally connects itself with the end hanging down from the smaller pulley to form a closed block chain.

When a differential pulley is at work, we pull the chain that connected to the fixed pulley with a bigger diameter. The two fixed pulleys are turning round together. The length of the chain pulled up by the bigger pulley is longer than that of the chain hanging down from the smaller pulley, so the movable pulley will move upward slowly together with the load hanging on it.

Why can the differential pulley save labour?

Let R and r be the radius of the bigger fixed pulley and the smaller fixed pulley respectively, G be the weight of the load, and F the actuating force (Fig. 56).

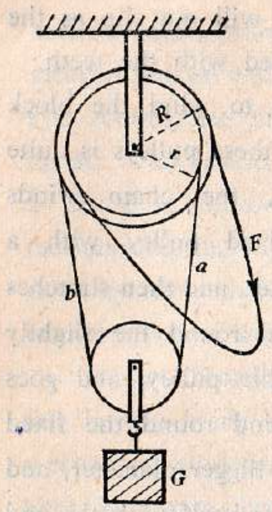

Fig. 56 Showing a differential pulley

When we pull the chain with an actuating force F to turn the bigger fixed pulley, the smaller fixed pulley will turn together with the bigger pulley because they are fixed to a common shaft. When F moves down a distance of $2\pi R$, the bigger fixed pulley will turn chain b upward with a length of $2\pi R$. At this time, the smaller fixed pulley will release down the chain a a length of $2\pi r$. The difference between the length winding up on the bigger fixed pulley and the length released down from the smaller fixed pulley is twice the height that the movable pulley and the load is lifted up. So, the height is $\frac{1}{2}(2\pi R - 2\pi r) = \pi(R - r)$.

Under the condition of neglecting the friction, the work done by the actuating force F is $F \times 2\pi R$ which is equal to the work done by the hands $G\pi(R - r)$, according to the mechanical work principle. Therefore,

$$F \times 2\pi R = G\pi(R-r)$$

thus
$$F = \frac{R-r}{2R} \times G$$

This is the equation for the actuating force to be used to actuate the differential pulley. From the equation, we can see that the longer the radius R of the bigger pulley is and the smaller the difference (R-r) between the radius of the bigger pulley and the radius of the smaller pulley is, the more the labour will be saved for a differential pulley. If the radius R of the bigger pulley is already set, we can make the smaller pulley with a radius r so that the difference between R and r is very small. This differential pulley can be very labour-saving.

For example: When $R = 15$ cm, $r = 14.5$ cm, the weight of the load $G = 1500$ kg, let us find out the actuating force to be used to pull up the load at a constant speed by using this differential pulley.

Substitute the figures mentioned above into the equation for calculating the actuating force F of a differential pulley. We can get

$$F = \frac{R-r}{2R} \times G = \frac{(15-14.5)\text{cm}}{2 \times 15\text{cm}} \times 1500\text{ kg}$$

$$= \frac{0.5}{30} \times 1500\text{kg} = 25\text{kg}$$

By using this kind of differential pulley, we need only 25kg of force to pull up a 1500-kg load at a constant speed. It is obvious that the differential pulley is a kind of mechanism which can save a lot of labour.

Well, as this differential pulley need only $\frac{25\text{ kg}}{1500\text{ kg}} = \frac{1}{60}$ of force, then if we want to lift up the load one metre high at a constant speed, how long the block chain we should pull?

Let S be the length of the block chain that we should pull in order to lift up the load one metre high. Let W_1 be the

work done by the pulling force applied to the chain. We have

$$W_1 = F \times S = 25\text{kg} \times S\text{m}$$

Let W_2 be the work done by pulling up the load by hand. Then in order to lift up the load one metre high, we have $W_2 = G \times 1\text{m} = 1500\text{kg} \times 1\text{m}$

According to the mechanical work principle, $W_1 = W_2$, i.e. $25\text{kg} \times S\text{m} = 1500\text{kg} \times 1\text{m}$

Therefore $S = \dfrac{1500 \text{ kg}}{25 \text{ kg}} \times 1\text{m} = 60\text{m}$

The answer reveals the fact that one has to pull the block chain 60 metres long to lift up a load of 1500 kg one metre high by using this kind of differential pulley. In this case, the load will rise at a very slow speed. So, if we want to select the adequate values for R and r when making use of a differential pulley, the actual situation has to be considered.

However, a differential pulley is a popular mechanism for lifting heavy loads. It is because one may use little effort to lift up a very heavy load. That's why people like to call it "The Magic Bottle Gourd".

CHAPTER VI

INCLINED PLANES

An inclined plane, one of the commonly seen mechanisms, is quite convenient to use. It is mainly for saving labour.

A plane, with one end at a lower position and another end at a higher position, is called an *inclined plane*.

By making use of an inclined wooden plane with one end attached to the platform of a truck, we can easily push a heavy load up onto the truck. It can save a lot of labour as compared with lifting the heavy load up onto the truck directly from the ground (Fig. 57).

China's magnificent Nanjing Yangtze River Bridge has a

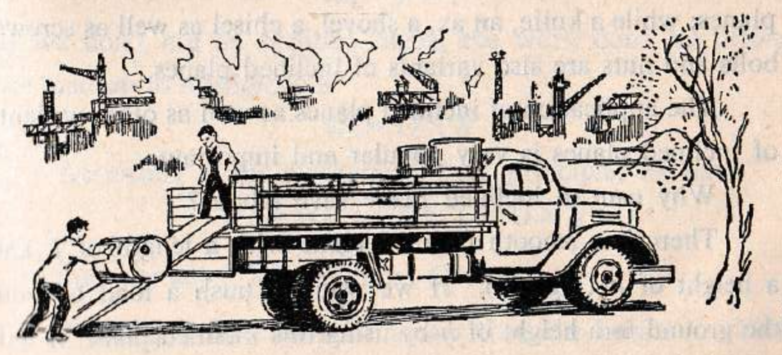

Fig. 57 Loading a truck by making use of an inclined plane

very long bridge approach which is an example of the long inclined plane (Fig. 58).

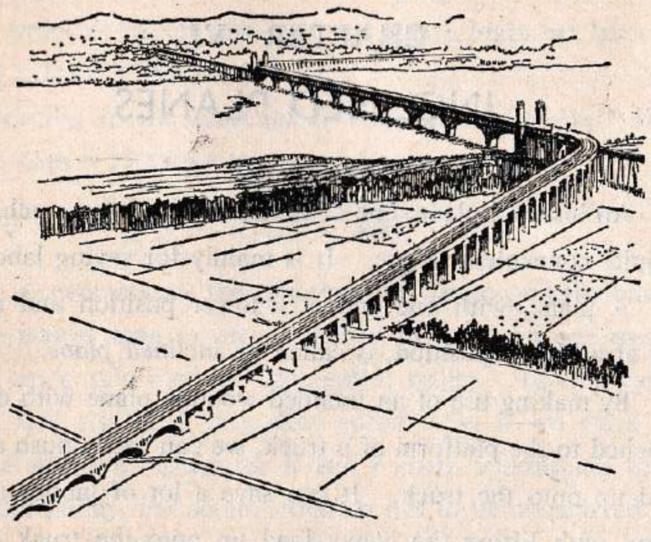

Fig. 58 The magnificent Nanjing Yangtze River Bridge

A winding mountain highway, the handrail of stairs, and the mountain slope for skiing are the application of inclined planes; while a knife, an ax, a shovel, a chisel as well as screws, bolts and nuts are also variants of inclined planes.

The application of inclined planes as well as other variants of inclined planes is very popular and important.

Why can an inclined plane save labour?

There is a smooth inclined plane with a length of L and a height of h (Fig. 59). If we want to push a load G from the ground to a height of h by using this inclined plane, it will save a lot of labour as compared with lifting it up directly

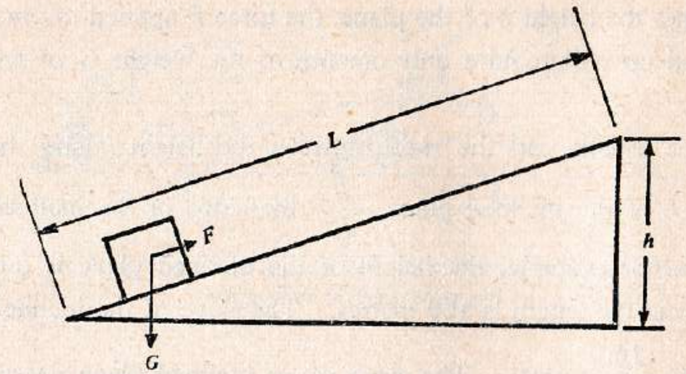

Fig. 59 Showing an inclined plane

from the ground. Why can it save labour? How much labour can it save?

Since inclined plane is a kind of mechanism, so it also observes the mechanical work principle.

Let F be the force to push a load up along an inclined plane at a constant speed, and G be the weight of the load. Hence, the work done by force F to push the load up to the top of the plane is

$$W_1 = F \times L$$

If we don't use an inclined plane, the work done by lifting the load up to a height h is

$$W_2 = G \times h$$

According to the mechanical work principle, we have

$$W_1 = W_2, \text{ i.e. } F \times L = G \times h$$

and then we get $\quad F = \dfrac{h}{L} \times G$

The length of L must be longer than the height h. This is why it can save labour. If the length L of the inclined plane

is n times the height h of the plane, the force F applied to push the load up will require only one-nth of the weight G of the load.

We usually call the ratio between the height h and the length L of the inclined plane $\frac{h}{L}$ the slope of the inclined plane. For example, the height of the inclined plane is one metre and the length is 100 metres. The slope of the inclined plane is $\frac{1\text{m}}{100\text{m}}=0.01$. The slope of an inclined plane resembles the degree of inclination. The smaller the slope is, the less the inclination will be; and the greater the slope is, the steeper the plane will be. The maximum value of slope is 1. The angle between this plane and the ground is 90°, so it is actually a vertical plane.

From the equation of the labour-saving inclined plane, we can see that when the weight of the load is ascertained, the greater the slope is, i.e. the greater the value of $\frac{h}{L}$ is, the less labour will be saved; and the smaller the slope is, i.e. the smaller the value of $\frac{h}{L}$ is, the more labour will be saved.

As it is shown in Fig. 60, there are several inclined planes with same height but different length. The longer the length of the inclined plane is, the more labour will be saved; and the shorter the length of the plane is, the less labour will be saved. It is also because their slopes are different.

Sometimes we also express the slope of the inclined plane by the degree of the angle between the inclined plane and the

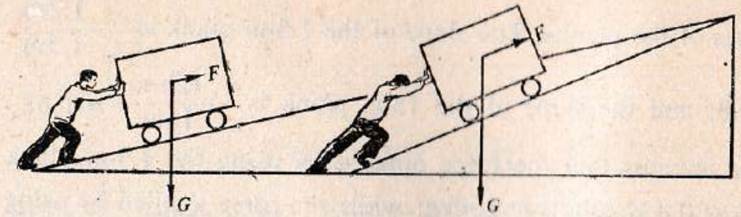

Fig. 60 The difference in labour-saving with same height but different length of plane

ground. It is called the angle of dip of an inclined plane. With same height, the smaller the degree of the angle is, the more labour will be saved.

When we are making use of the inclined plane, we cannot only seek after labour-saving and neglect other factors. Of course, when the angle of dip is equal to 0°, it is the most labour-saving position. However, this plane is not inclined, it is in the levelling position. If the angle of dip of an inclined plane is rather small, then we have to spend more time to travel a rather long distance in order to push up a load to a rather low height, although it saves a lot of labour. It is not economical.

For example: Try to push a 200-kg load up at a constant speed onto a truck platform with a height of 1.2 m. There are two planks with a length of 1.5 m and 15 m respectively. What are the respective forces to be applied to push up the load?

According to the labour-saving equation for inclined planes, $F=\frac{h}{L}\times G$, let us calculate the respective

slopes of the planks. The slope of the 1.5-m plank is $\frac{1.2\text{m}}{1.5\text{m}}$ $= 0.8$; and the slope of the 15-m plank is $\frac{1.2\text{m}}{15\text{m}} = 0.08$. It is obvious that the force applied by using the 1.5-m plank is $F_1 = 0.8 \times 200$ kg $=$ 160kg; while the force applied by using the 15-m plank is $F_2 = 0.08 \times 200\text{kg} = 16\text{kg}$. The force applied by using the short plank is ten times that by using the long plank. Nevertheless, we have to travel 15 metres on the long plank but 1.5m on the short plank. The long plank can save labour but not distance.

CHAPTER VII

TWO OTHER KINDS OF INCLINED PLANES—WEDGES AND SCREWS

Wedges and screws are other kinds of common inclined plane mechanisms.

Wedges are very useful in many ways, such as, a knife, an ax, a shovel, a chisel. Wedges can be used to lift up a very heavy load or to apply great pressure to an object.

Screws are widely used in our daily life, such as, a wood screw, a bolt and a nut. They can be used to lift a heavy load or to apply pressure to an object, too.

Wedges

The vertical section of a wedge is in the shape of a right-angled triangle or an isosceles triangle (Fig. 61).

When a wedge is driven home by a force F into an object, we may assume that the wedge enters the object in length h under a force F. The work done by the actuating force is equal to $F \times h$. At the same time, the object is split apart by the wedge and the width is h_1. It is obvious that h_1 is perpendicular to the inclined plane of the wedge. The force acting on the two sides of the wedge from the object is the resistance

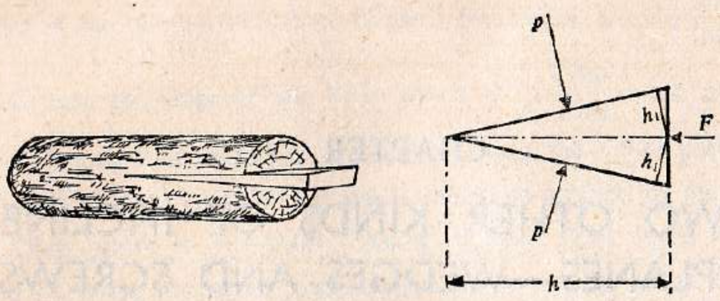

Fig. 61 Studying the work of a wedge

force P which is also perpendicular to the inclined plane of the wedge. According to the mechanical work principle, the work done by the wedge to overcome the resistance force is equal to $P \times 2h_1$, so we have

$$F \times h = P \times 2h_1$$

hence

$$F = \frac{2h_1}{h} \times P$$

Since h is much greater than h_1, therefore, F must be smaller than P. This is why a wedge is a labour-saving mechanism.

The longer the wedge is, the sharper the thin edge of the wedge will be. That is to say, if h becomes greater, h_1 will become smaller, and it will save more labour. But, if we want to split the object $2h_1$ in width, the wedge have to drive into the object much deeper.

A chopper, a sickle and a knife for pencil-sharpening should be designed with the purpose of saving labour, therefore, their inclined planes are very long, and their thin edges are very sharp, i.e. h is much greater than h_1.

Wedges can be used to reinforce an object, lift an object up and apply a pressure to an object (Fig. 62).

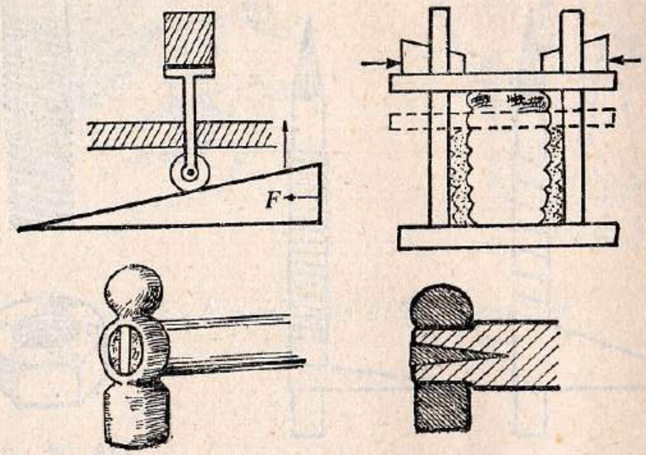

Fig. 62 Showing a wedge can be used to reinforce an object, to lift up an object or to apply a pressure to an object

Screws

Cut a piece of paper to form an inclined plane in shape and roll it around a pencil. A pattern of a thread will be formed around the pencil (Fig. 63). The smaller the slope of the inclined plane is, the finer the pattern of the thread will be. A screw is an inclined plane wound around a cylindrical rod or a cone.

The thread outside of the bolt is called a male thread. The thread inside a nut is called a female thread (Fig. 64).

When it is necessary to lift up a very heavy object to a comparatively low height, we usually use a screw instrument

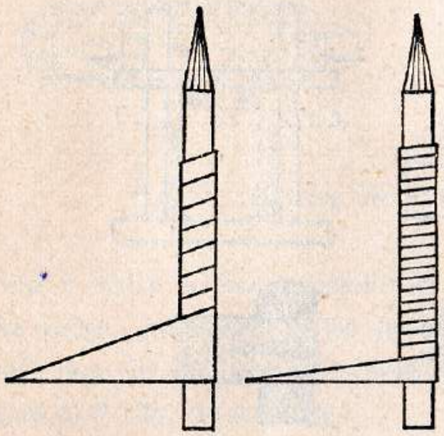

Fig. 63 *Making a thread of a screw*

Fig. 64 *A bolt and a nut*

to accomplish the task. For example: A sluice gate in a dam in the countryside can be lifted up by using a screw installation. When people want to change a flat tyre from a truck, they usually use a screw jack to jack up the car. A screw jack is a typical screw installation to lift up a heavy truck with only a small force (Fig. 65). Why can a screw save labour? We can also analyse it by applying the mechanical work principle.

In Fig. 66, there is a diagram showing a screw device to lift a load up. Let L be the length of distance between one end of the handle and the screw thread, and let F be the actuating force acting on the handle in a circular motion. Hence, when the screw turns a round, the work done by the actuating force F is $F \times 2\pi L$.

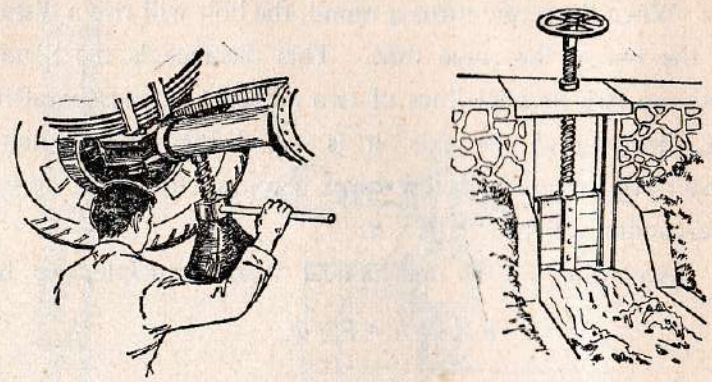

Fig. 65 *A sluice gate and a screw jack*

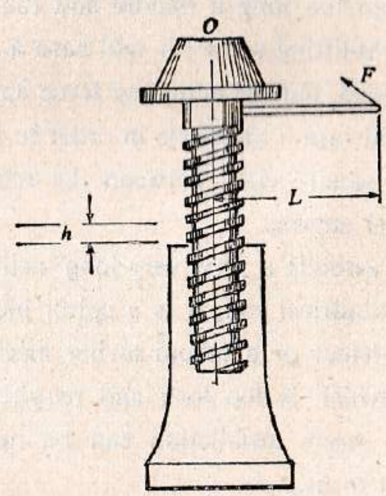

Fig. 66 *A diagram showing a weight-lifting screw at work*

When the screw turns a round, the bolt will rise a distance in the nut at the same time. This distance is the distance between two parallel lines of two adjacent threads parallel to the direction of the axis, it is called the thread pitch h. Therefore, when the screw turns a round, the work done by overcoming weight P is $P \times h$.

According to the mechanical work principle, we have

$$F \times 2\pi L = P \times h$$

hence,

$$F = \frac{h}{2\pi L} \times P$$

Owing to the fact that L is greater than h, therefore, the actuating force F is much smaller than weight P. So, we can use a little actuating force to lift up a very heavy object.

If we design too long a handle and too small a thread pitch for a weight-lifting screw, it will save a lot of labour to lift up a heavy load, but the actuating force applied to the end of the handle will turn a big circle in order to lift a very heavy load up a very small height between the screw threads. It is not economical anyway.

A screw is actually a very, very long inclined plane winding around a cylindrical rod, it is a spiral inclined plane. It overcomes the defect of a labour-saving mechanism with an inclined plane which is too long and requires too bulky an installation. A screw installation can be made lighter and more convenient to use.

By making use of the screw working principle, people make wood screws, bolts, nuts and squeezers (Fig. 67).

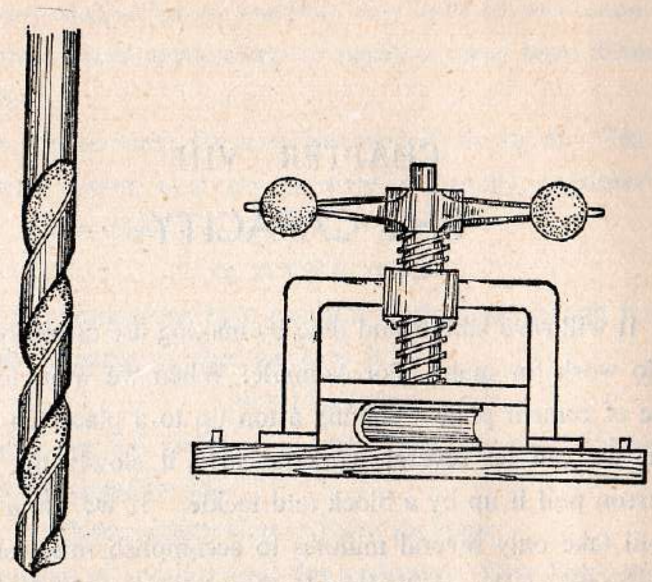

Fig. 67 A bit of a drill and a squeezer

CHAPTER VIII
THE CAPACITY

It will save labour and time by making use of mechanisms to do work for man. For example: When we want to lift a piece of cement plate weighing a ton up to a place ten metres high, we can let several workers carry it slowly up, or let a person pull it up by a block and tackle. If we use a crane, it will take only several minutes to accomplish this task. The magnitudes of the work done by these three methods are the same. But the speed in doing this job is different greatly. For the same type of mechanisms, the working speed is also different. For example: To push a heavy object onto a certain height by making use of an inclined plane, the time required to push up an inclined plane with a greater slope is shorter than that with a smaller slope. How to express the speed of a mechanism in doing a work? The capacity of the work done by mechanisms is expressed by the amount of work done during a definite period of time. Thus we have the concept of capacity.

The amount of work done per unit time is called *capacity.*

If we use W to be the work done by the mechanism during a period of time t, the equation of the capacity N is

$$N = \frac{W}{t}$$

Every mechanism or machine may have its own capacity. Different kinds of mechanisms or machines may have different capacities.

For engineering, the unit for capacity is kg·m. The international system unit for capacity is usually expressed in joules. Their relation is

$$1 \text{ kg}\cdot\text{m} = 9.8 \text{ joules}$$

If the work done by a machine during one second is one joule, the capacity of this machine is

$$\text{N} = 1 \text{ joule/sec}$$

In physics, we call joule/sec as watt. We may use kilowatt as the unit for capacity that

$$1 \text{ Kw} = 1000 \text{ watt} = 1000 \text{ joule/sec}$$

Horse-power is another unit for capacity. One horse-power is about 735 W. The so-called horse-power does not really mean the power of a horse and it is not the capacity for a horse. When a horse is working for quite a long time, its capacity is around 0.4 to 0.6 horse-power. The working capacity for a man is about 0.05 to 0.1 horse-power. When a weight lifter is lifting up the disk loading bar bells, its capacity may sometimes exceed two horse-powers.

There is a data plate for every machine. On the data plate, we can find the data for the characteristics of its structure and its function. Capacity is one of the data. It is quite important to know the capacity value of a machine so as to use it adequately. For example: There is a water pump with a capacity of 5.5 Kw, and we want to get an electric motor to operate it. If we use an electric motor with a capacity of

4 Kw, the water pump cannot work properly. If we use an electric motor with a capacity of 7.5 Kw, the electric motor cannot be fully used according to its capacity. An electric motor with a capacity of 5.5 Kw is an ideal one. Such a combination of the water pump and the electric motor can make them work normally and do the job in full capacity.

When a machine is at work, there will be a working force acting on the object, making it moving at a certain speed. For example: A crane is lifting up a load which is rising gradually at a certain speed. The rising speed of the load shows the speed of work done by the crane. So, we are certain that the capacity of the mechanism must have something to do with the operating speed. The relationship between the capacity and the speed as well as the working force can be derived from the following equations:

Because capacity $N = \frac{W}{t}$

but work $W = F \times S$

therefore $N = \frac{W}{t} = \frac{F \times S}{t} = F \times \frac{S}{t}$

While $\frac{s}{t}$ is the moving velocity V of the load, the above equation can be rewritten as follows: $N = F \times v$

This relationship shows that when the capacity of the mechanism is certain, if we want to increase the actuating force, the moving velocity of the object must be slowed down, i.e. the ratio between the actuating force and the velocity is an inverse ratio. For instance: When the capacity of the engine of a motor car is fixed, if the car is climbing up a slope, we

must increase its traction force, and as a result, the velocity of the car must be decreased. But, if the motor car is running on a level road, it needs only a small traction force and the car can run faster. This characteristic of a mechanism is called the characteristic of a horse or a bull. It is slow but powerful just like a bull; and it is speedy but not so powerful just like a horse.

For example: The *Liberation* truck manufactured in China has a capacity of 90 horse-powers. If its traction force is 675 kg, what will be the distance travelled by the truck in three minutes? What is its velocity?

We know $N = 90$h.p. $t = 3$min. $F = 675$kg

to find S and v

First, we have to unify the units according to the requirements. We have

$N = 90$ h.p. $= 66150$ watt

$t = 3$ min. $= 180$ sec

$F = 675$ kg $\times$ 9.8 $= 6615$ newton

It is because the equation for a motor car to do a work is $W = F \times S = 675\text{kg} \times S\text{m}$. So, we have to change kg/m into joule, thus

$675 \times S\text{kg/m} = 675 \times S \times 9.8$ joule $= 6615 \times S$ joule

Then we can substitute capacity and force and velocity into the equation.

Because $N = F \times \frac{S}{t}$

therefore $S = \frac{N \times t}{F} = \frac{66150 \times 180}{6615} = 1800$ m

But $v = \frac{S}{t}$

therefore $v = \frac{S}{t} = \frac{1800}{180} = 10\text{m/sec}$

The truck travelled 1800 metres in three minutes at a velocity of ten metres per second.

CHAPTER IX

MECHANICAL EFFICIENCY

In fact, when we introduce the mechanisms, a lever, a pulley or an inclined plane, we usually treat it in an idealistic way. We do not consider the weight of the lever itself and the friction force between the lever and its fulcrum. When we are discussing a pulley, we do not consider the friction forces between the pulley and the rope as well as between the pulley and the shaft, and the weight of the rope. When we are making use of an inclined plane, we do not include the friction between the object and the inclined plane in our calculation.

However, in practice, these neglected parts are actually existed. Sometimes, they play an important role in the actual situation that we cannot neglect them.

What can these theoretically neglected factors affect the practical work? For example: When we use a block and tackle to lift up a load, the weight of the load is the resistance force which should be overcome. This is the useful resistance force. But the frictions between the rope and the pulleys and between the shafts and the pulleys are all other kinds of resistance forces, which are called extra resistance forces. Of

course, these are not the only extra resistance forces. At the time when the load is lifted up, the movable pulley will also be lifted up. The weight of these movable pulleys is also an extra resistance force. Besides, the weight of the load being lifted up by the crane is considered to be the useful resistance force, while the frictions between the rope and the pulleys as well as the shafts and the pulleys and also the weight of the horizontal beam of the crane are all extra resistance forces.

It is obvious that when the mechanism is doing a work, the work done by the mechanism must overcome the useful resistance force (a necessary load) and the extra resistance forces as well (cannot be evaded). We always hope to make a more efficient mechanism, i.e. try our best to reduce the extra resistance force so that it needs less work to overcome the extra resistance force.

Generally, the work done to overcome the useful resistance force is called the useful work; while the work done to overcome the extra resistance force is called the extra work. The work done to overcome the total resistance force is equal to the sum of the useful work and the extra work.

According to the mechanical work principle, the work done by the actuating force towards the mechanism must be equal to the work done to overcome the total resistance force. People usually call this actuating force as the total work done by the mechanism. Therefore, we let W be the total work, W_1 be the useful work and W_2 be the extra work. The mechanical work principle can be expressed as follows:

$$W = W_1 + W_2$$

If the useful work of a mechanism takes a bigger share in the total work, this mechanism can use less force to do more useful work. In other words, if the extra work of this mechanism is rather small, most of the total work is used for the useful work. This mechanism is considered to be an efficient one.

The term in physics to express the efficiency of a mechanism is called mechanical efficiency. Its definition is as follows: The percentage of the useful work in the total work. It is mathematically expressed as follows:

$$\eta = \frac{W_1}{W} \times 100\% \quad (\eta \text{ is the mechanical efficiency.})$$

All mechanisms have frictions. So, there is no mechanism without extra work when the mechanism is at work. Therefore, the useful work is always smaller than the total work. The mechanical efficiency for any mechanisms is always less than 100%. For example: The mechanical efficiency is around 40 — 50% for cranes, 50 — 60% for blocks and tackles, and 60 — 80% for water pumps.

It is the most important problem in our practical work to raise the mechanical efficiency so that the mechanism could do more useful work by consuming a definite amount of actuating force. The usual way is to reduce friction by installing bearings, adding lubricating-oil or making the inclined plane flat and smooth, or sometimes by improving the mechanical structure or decreasing its own weight, in order to reduce extra work as much as possible so as to attain the aim of raising the mechanical efficiency.

The mechanical efficiency can be expressed by the percentage of useful work in the total work, and it can also be expressed in terms of capacity.

Let N be the total capacity of the mechanism, N_1 the useful capacity. Because the total work $W = N \times t$, the useful work $W_1 = N_1 \times t$, therefore

$$\text{efficiency} \quad \eta = \frac{W_1}{W} \times 100\% = \frac{N_1 t}{N t} \times 100\%$$

$$= \frac{N_1}{N} \times 100\%$$

The mechanical efficiency is the percentage of the useful work in the total work.

For example: A crane lifts a cargo weighing 9.6 tons up to a height of 20 metres in two minutes. We know the total capacity of the crane is 20 Kw. The questions are: What are the total capacity, the useful capacity, and the extra capacity of the crane? What are the useful efficiency and mechanical efficiency of the crane?

We know

$P = 9.6$ ton, $h = 20$m,

$t = 2$ min. $N = 20$Kw

to find W, W_1, W_2, N_1 and η

Solution: Unify the units used.

$P = 9.6 \text{ ton} = 9600\text{kg}$

$t = 2 \text{ min} = 120 \text{ sec}$

$N = 20 \text{ Kw} = 20{,}000 \text{ w} = 2 \times 10^4 \text{ watt}$

(1) To find the total work W

$W = N \times t = 2 \times 10^4\text{w} \times 120 \text{ sec}$

$= 2.4 \times 10^6$ joule

(2) To find the useful work W_1

$W_1 = P \times h = 9600\text{kg} \times 20\text{m}$

$= 1.9 \times 10^5 \text{ kg}\cdot\text{m} = 1.9 \times 10^6$ joule

(3) To find the extra work W_2

$W_2 = W - W_1 = 2.4 \times 16^6\text{J} - 1.9 \times 10^6\text{J}$

$= 5 \times 10^5$ joule

(4) To find the useful capacity N_1

$$N_1 = \frac{W_1}{t} = \frac{1.9 \times 10^6\text{J}}{120 \text{ sec}} = 1.6 \times 10^4 \text{ watt}$$

$$= 16\text{kw}$$

(5) To find the efficiency of the crane η

$$\eta = \frac{W_1}{W} = \frac{1.9 \times 10^6\text{J}}{2.4 \times 10^6\text{J}} \times 100\%$$

$= 79.2\%$

Or, $$\eta = \frac{N_1}{N} = \frac{16\text{Kw}}{20\text{Kw}} \times 100\%$$

$= 80\%$

The final results of the mechanical efficiency calculated by using two methods are not the same. It is because when we calculate W, W_1 and N_1, we use the approximate values. So, we may consider the results calculated from these two methods are the same.